Athletic Footwear and Orthoses in Sports Medicine

Second Edition

Matthew B. Werd
E. Leslie Knight
Paul R. Langer
Editors

Springer

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Foreword

As the Preface to this second edition of *Athletic Footwear and Orthoses in Sports Medicine* tells us the intent:

> is to provide sports medicine practitioners from all backgrounds and training—which include physicians (MD, DO, DPM, DC), athletic trainers (ATC), physical therapists (PT, DPT), researchers (MA, PhD), massage therapists (LMT), and anyone involved in the treatment of athletes, including members of the Independent Running Retailers Association (IRRA)—with an updated, contemporaneous, and practical book, which will help to optimize the care and performance of the athlete.

This goal is achieved. The book covers it all, from the complex science that underlies those underlayments found in many an athletic shoe of many athletes, the orthosis, to the aim of, as the authors say at the beginning of the chapter on "Prescribing Athletic Footwear and Orthoses," "maximizing athletic performance and minimizing injury through the use of an appropriate prescription for athletic footwear and orthoses." And it actually begins, appropriately enough in the first chapter, with a history of running shoes, in fact, believe it or not going back 10,000 years running footwear. This is complemented in the second chapter, which is an expanded consideration of the development of orthoses, over time. This kind of attention to detail in one dimension and comprehensiveness in the other characterizes the whole book and it attention to its subject.

To the best of the editors' knowledge, the first edition of this book was the first of its type. And the editors, Drs. Matthew Werd, Paul Langer, and E. Leslie Knight (deceased), have once again done an outstanding job in assembling a talented, knowledgeable, and experienced group of authors for their effort.

Speaking as someone who has owned a wide variety of athletic shoes, for running, PaceWalking™, cycling, downhill skiing (and still does) and does not take a step in any of them without an orthosis between my foot and the shoe's insole, I was fascinated to discover how much there is to know and learn about this subject.

As noted above, for example we learn in some detail the history of the development of the modern running shoe, whose development goes back to the time of the Ancient Greeks. There is a comprehensive review of the history and literature on the development of orthoses, a theoretical and practical science that continues to evolve. There is a whole chapter devoted to the design and characteristics of the various types of athletic socks. Separate chapters detail virtually every type of specialty athletic footwear, from the running shoe to the snowsport boot (downhill, cross-country skiing, and snowboarding, each with a separate chapter), to shoes for golf, tennis, basketball, other court sports, and even cheerleading. Central to the book is Dr. Werd's very detailed chapter on the insights on prescribing athletic footwear, shoes and orthoses, and the role of athletic footgear in the prevention of injuries.

This book will indeed be useful for all health professionals who deal with patients who are athletes of one kind or another. All sports other than swimming require a shoe of one kind or another. Many patients and clients who are athletes, or thinking simply of becoming regular exercisers, will have questions about shoes and about orthoses. Many who might benefit from the latter do not know about them or might think that one bought from a drugstore shelf will do the trick when indeed that is not the case. While for the podiatrist this book presents a good deal of technical information in one place, for the non-podiatric health care provider this book provides very helpful information on when and how to make appropriate referrals. Some chapters provide the detail required by the specialist, while others provide more general information useful to all potential readers.

Finally, this book does not have to be read through to be very helpful, and in fact most readers will likely not read it from cover to cover. Therefore, the repetition of essential information that does appear in various chapters is very useful, for that repetition increases the chances that every reader will get to see it. Whether your patient is looking for basic comfort, improved performance, or injury avoidance/prevention/treatment in their footwear, this is the guidebook for you.

Postscript: Les Knight was a dear friend of mine. For close to 20 years I was fortunate enough to be asked to participate in the annual wellness seminars that he put on at the Breckenridge Ski Area in Colorado. A gracious, funny, and very knowledgeable man and skilled teacher, he is already sorely missed by anyone who knew him, certainly including myself.

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Preface

The first edition of *Athletic Footwear and Orthoses in Sports Medicine* filled a much-needed void as the original comprehensive, evidence-based resource on athletic footwear and orthoses for the entire sports medicine team. The importance of filling this void has been reflected by the overwhelming success in the first edition's large distribution of print copies, but more so by it reaching the top 25% of most downloaded e-books in the Springer e-Book Collection, Springer being one of the largest publishers of medical books in the world.

The intent of this second edition of *Athletic Footwear and Orthoses in Sports Medicine* is to take the first edition to the next level with an updated contemporaneous, practical book for sports medicine professionals from all backgrounds and training, including physicians (MD, DO, DPM, DC); athletic trainers (ATC); physical therapists (PT, DPT); researchers (MA, PhD); massage therapists (LMT); and members of the Running Industry Association (RIA- formerly the Independent Running Retailers Association, or IRRA), and all others involved in the care of athletes. The content of this book will help optimize the care and performance of the athlete.

We were originally approached to edit this text as a result of the overwhelming interest stimulated on this topic through extensive lectures and workshops, which have been presented at the American College of Sports Medicine (ACSM) regional and national meetings, as well as workshops and meetings presented by the American Academy of Podiatric Sports Medicine (AAPSM). This text should serve as a resource to continue to educate sports professionals to make an informed, evidence-based decision on recommending and prescribing athletic footwear and orthoses, as well as to provide insight to appropriate referral to a specialist.

The approach to this second edition has been to continue to include as much evidence-based medicine as available, and contributors have referenced the most current studies and literature. The science and research is available that clearly documents the efficacy of functional foot orthoses in the treatment of lower extremity biomechanical pathology. The use of proper athletic footwear and orthoses has been shown to optimize an athlete's performance, as well as to help limit the risk of certain injuries.

Many of the first edition chapters have been updated with fresh content and current resources, such as Dr. Kirby's chapter, "Evolution of Foot Orthoses in Sports," which has added 52 new references (from 93 to 145 references) and an additional 1329 words (from 4262 to 5593 words). This new chapter is contemporaneous and certainly represents one of the most comprehensive analyses of the history, research, and theory behind foot orthoses that exists within the scientific literature to date.

The first edition chapter “Prescribing Athletic Footwear and Orthoses: The Game Plan” has been significantly updated and renamed “Insights on Prescribing Athletic Footwear and Orthoses: The Game Plan” and is a must-read. This updated chapter incorporates many of the other individual topics from this book into a succinct protocol on formulating an appropriate athletic shoe recommendation. Additionally, many current references and new insights on the direction of the athletic shoe industry are discussed.

New chapters have been added to expand areas, which were limited in the first edition, including “Clinical Gait Analysis for the Athlete”; “Golf”; “Tennis”; and “Nordic Skiing.” Also, a new extensive “Cycling” chapter has been added, which provides a comprehensive discussion on different types of cycling, equipment, and shoe gear for lower extremity injury prevention.

An entirely new part titled, “Running Footwear,” has been added in response to the explosion of new running shoe technologies and concepts. New chapters in this part include “Barefoot, Minimalist, Maximalist, and Performance”; “Footwear and Cross-training”; and “Racing Track and Cross-country.” The “Barefoot, Minimalist, Maximalist, and Performance” chapter has some of the most significant and inclusive content ever published on this evolving topic, and it includes an exhaustive review and inclusion of contemporaneous research and literature.

We are also excited to reach out to the members of the Running Industry Association (formerly the Independent Running Retailer Association, or IRRA), specialty retailers who are on the frontline of fitting and dispensing athletic footwear, and who are integral in the comprehensive care of the athlete. The new chapter “Specialty Running Stores and the Sports Medicine Professional: A Natural Partnership” aims to continue to foster the win-win-win relationship between the sports medicine professional, running retail specialist, and athlete. Developing a good working relationship with a local running retailer is critical for the sports professional, and chapter contributor Rich Wills—owner of a “Top 50 Best Running Store in America” and former IRRA Board member—does an excellent job of presenting the importance of bridging the gap from the doctor’s examination room to the specialty-retail running shoe wall.

Another important new part has been created, “Special Populations and Athletic Footwear.” In addition to including an updated “Special Olympics” chapter by Patrick Nunan, DPM, we welcome the addition of a new chapter titled, “Pediatric Footwear,” written by Mark Cucuzzella, MD. Dr. Cucuzzella discusses and addresses many of the questions that often perplex parents, coaches, and sports medicine professionals regarding children and footwear recommendations.

The American Academy of Podiatric Sports Medicine (AAPSM) continues to be represented prominently throughout this text and has provided the majority of chapter contributors through its members, fellows, and past presidents. Since its inception in the early 1970s, AAPSM and founding members Drs. Robert Barnes, Richard Gilbert, John Pagliano, and Steven Subotnick have been and continue to be a reliable and unbiased source for current athletic footwear information and education.

Please visit the Academy's website, www.AAPSM.org, for the most up-to-date athletic footwear information and resources.

We hope that this updated second edition text will continue to be a valuable, reliable, and practical resource on athletic footwear and orthoses in sports medicine for the entire sports medicine team.

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Acknowledgements

**The last conversation that I had with "Les" (Dr. E. Leslie Knight) was about how excited and proud that he was, that we were in the final stages and near completion of this outstanding book. Les then passed away unexpectedly just before this manuscript was finalized and sent for publishing, but his contributions will live forever. In life, we only come across a handful of true mentors: friends who have reached the pinnacle of their profession; those who always exude positive feelings with genuine inspiration and encouragement; those who are humble in their tremendous accomplishments; and those who possess that innate sense to lead and bring others along for the ride. This was Les, one of my greatest mentors: a reliable friend; an esteemed colleague; a fellow ACSM-Fellow; an avid lifelong exercise enthusiast; and a tremendous person. This one's for you, Les!*

Special thanks *again* to Steven Jonas, MD, PhD, for his critical review of the manuscript and his succinct comments in the Foreword. Steve and Les were best of friends, and Steve also certainly fits the above description as a true, once-in-a-lifetime mentor. Thank you Steve, on behalf of Les and myself.

Dr. Paul Langer has been added as our third author for this second edition, and what a tremendous asset Paul has been. Dr. Langer has brought his lifelong experiences and training to this text, which includes his unique perspectives and tremendous insights on athletic footwear. Dr. Langer is a past president of our American Academy of Podiatric Sports Medicine, he has academic affiliations in an orthopedic group practice, he is a frequently published author on athletic shoes, he works closely within a running specialty retail store, and he is an avid lifelong exercise enthusiast. Paul's contributions have been outstanding in the review, corrections, and insights of this manuscript throughout the entire process—great work Paul!

Each contributing chapter author for this second edition has been selected or reselected for their recognized expertise and experience as leading educators and practitioners in the area of athletic footwear, orthoses, and lower extremity biomechanics. The tremendous time commitment and effort given by each contributor in order to help educate and benefit the general sports medicine profession has been incredible. Each contributing chapter author is to be commended.

A number of extremely talented individuals who share a passion for sports medicine have provided both inspiration and motivation in pursuing a career in sports medicine. Credit goes especially to my mentor during my surgical residency program—my residency director at South Miami Hospital, Dr. Keith B. Kashuk, for his positive influence on my sports medicine and surgical career and for his commitment as an educator—always challenging students, residents, and physicians to be their best.

The American Academy of Podiatric Sports Medicine's (AAPSM) members, fellows, board members, and past presidents should be recognized and commended for their enthusiasm and continued support of the Academy and its mission. Special thanks to Dr. James Losito who provided me early guidance and opportunities within the Academy, as well as colleagues including Drs. Edward Fazekas, Marvin Odro, Timothy Dutra, Gerald Cosentino, Rich Bouche, and Douglas Richie. AAPSM's Executive Director, Rita Yates, has been a steadying force and tremendous resource, and Rita was recently inducted as a member into the Podiatry Management Hall-of-Fame. Congratulations and thank you Rita for the lifelong friendship and commitment to the Academy.

The American College of Sports Medicine (ACSM) provides an opportunity to interact and collaborate with sports professionals from diverse fields, all of whom share the same common passion for sports medicine. Several key individuals should be recognized for their guidance, friendship, and inclusion of podiatric sports medicine, including Drs. E. Leslie Knight, Steven Jonas, MD, PhD, William Roberts, MD, Robert Sallis, MD, and Jeffery Ross, MD, DPM.

I also am grateful to my colleagues at Florida Southern College and the athletic training program and medical staff for including me as part of the outstanding sports medicine team, especially Sue Stanley-Green, ATC, Al Green, ATC, and Mick Lynch, MD.

I am most grateful to my parents, my sister and brother, and to my wonderful wife Heather and to my children Madalyn, Matthew, and Melody. Their smiling faces continue to provide inspiration each and every day, and they provide a constant reminder of the value and importance of balance in life.

A special thanks to the editorial staff at Springer for their persistence and guidance on this project, including Sadie Foster who was instrumental in identifying the initial need for this text and for helping to lay the original framework, and to Kristopher Spring for his recognition of the success of the first edition and the need for an updated second edition. Lastly, Patrick Carr is to be recognized for his patience and tremendous work corralling all contributors together and providing day-to-day support.

Here's to looking forward to the third edition, Cheers!

Matthew B. Werd, DPM

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Part I

Fundamentals of Athletic Footwear and Orthoses

Evolution of Athletic Footwear

1

Steven I. Subotnick

History of the Running Shoe

Introduction

Shoes are vital to man's sole. It is no secret that feet manage the challenges of daily life with the help of shoes. Shoes can stabilize, allow for flexibility or rigidity, cushion, and, in some cases, even injure feet. With the evolution of fast paced lifestyles, shoes have been scientifically engineered to provide the most comfort and to perform at the highest level for the individual who wears them, but shoes have not always been as systematically constructed.

The earliest footwear ever recorded was discovered by Luther Cressman inside Fort Rock Cave in Oregon and dated to the end of the last ice age, making it almost 10,000 years old [1]. The simple construction incorporated sagebrush bark knotted together, creating an outsole with ridges for traction, a covering for the forefoot, and straps to go around the heel. Although people did not devote much attention to detail when making shoes in the past, even early human beings realized that a basic piece of material covering their feet could afford them the opportunity to explore a larger part of their world.

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Ancient History

As the Olympics gained much success in a remarkable empire, the society began to devote more attention to shoes. Most ancient Greek athletes barely wore any clothes let alone running shoes, but these dedicated competitors began to observe that champions from colder climates wore race sandals [2]. Thus, the Greeks gave up the initial notion that their rivals were cheating and realized that this type of foot covering actually increased traction. As the popularity of competitive events in ancient civilizations grew, so did the advancement of running sandals.

The ancient Etruscans attached the sole of the sandal to the upper with metal tacks, while the Romans used tongs to wrap the shoe as close to the foot as possible to maximize traction [2]. The Romans ultimately excelled in shoemaking and created many styles from sandals to boots to moccasins. Personal commitment to athletic sovereignty and to the success of one's own empire drove the ancient Greeks and Romans to investigate ways to increase human performance through the use of manmade enhancements like shoes.

The Running Shoe Revolution

It wasn't until the seventeenth and eighteenth centuries in Britain that careful thought was once again given to sports and the running shoe. The first sports-specific shoe was not developed for running but for cricket [1]. The Spencer cricket shoe, a low-cut, leather construction with three spikes under the forefoot and one under the heel, was developed in 1861, and these spiked shoes became an essential part of competing. Then from 1864 to 1896 the sport of track flourished and runners began to compete with low-cut shoes made of kangaroo leather uppers, leather soles with six mounted spikes on the forefoot, and leather half-sole [1]. Once runners decided that the circular track was too confining, they took a step away from the track, began to run long distance races, and the running shoe took another leap forward.

Initially, marathon runners of the early Modern Olympic Games competed in heavy boots or shoes with leather uppers and soles, allowing for little plasticity. With the increasing popularity of the running events, the Spalding Company addressed the need for running shoes among the public and advertised a high-cut, black leather shoe with a reinforced heel and a sole of gum rubber, but the outsole did not last long and further improvements needed to be made [1]. In the 1940s, the famous marathon runners, Johnny Kelly and Jock Semple, were having serious problems with the crude manufacturing of their running shoes, so Richings, a retired English shoemaker, created a pair with a seamless toe box, laces on the side of the shoe, a separate heel, a low-cut rear part without a counter, and a repairable outsole [1]. The race of another sort was on as individuals from around the world joined in the shoemaking effort to see who could devise the better shoe.

Reebok Begins the Race

Joseph William Foster opened up a family-owned shoe business called J.W. Foster and Sons Limited in 1895 in Bolton, UK. This dedicated company made thin leather shoes constructed of rigid leather to be worn by Lord Burghley in the 1924 Olympics [2]. A notable advancement occurred when Foster's company began to stitch a leather strip around the top of the shoe [2]. However, in 1958 the grandsons of Foster, Jeffrey and Joseph, left their grandfather's business and conceived Reebok. The company's name originated from a Dutch word that refers to a type of antelope or gazelle. In the 1980s, Reebok explored the market of women's shoes by designing a flimsy but eye-catching shoe, and the aerobic era added to Reebok's faithful following [2]. The Reebok Freestyle was developed to be worn in or out of the gym. Later in the decade, Reebok created the Pump, consisting of an air bladder in the tongue of the shoe, to hold the ankle in a more fixed position.

The Amazing Dassler Brothers

In Germany, Adolf Dassler began making shoes in 1920 and was later joined by his brother, Rudolph. Their popular shoe was worn by successful German athletes and even donned by Jesse Owens in at least one of his races at the 1936 Munich Olympics [1]. Despite their success, a bitter family feud in 1948 divided the brothers, their small community in West Germany, and the thriving shoe company. Adolf Dassler created Adidas while Rudolph formed Puma, and the two companies have been competing in the runner's world ever since. Adidas assumed the trefoil sign that represented Adolf's three sons [1]. He used arch support lacing which is an early form of speed lacing and the classic, three stripes to help support the foot in his shoes [1]. On the other side of town, Puma chose the leaping puma as its logo to convey speed and power.

Tiger Shoes and ASICS Join the Chase

Onitsuka Co. Ltd. started constructing shoes in 1949. At the 1951 Boston Marathon, a young Japanese runner by the name of Shigeki Tanaka won the coveted race and displayed the Tiger shoes as he crossed the finish line. This shoe was designed with the traditional Japanese shoe, the Geta, in mind and had a separate compartment for the big toe. The shoe with the divided toe box could only be worn by Japanese athletes with a large space between the first and second digits [1]. Eventually, the shoe company known as Tiger became ASICS, which is a Latin acronym for "healthy mind in a healthy body."

New Balance and Intelligent Design

William J. Riley founded the Riley Company, the predecessor to New Balance, and began crafting shoes in the New England area in 1906. In 1961, the new owner of New Balance, Paul Kidd, took the experience he had gleaned from making orthopedic shoes, poured his knowledge into a running shoe, tested it scientifically, and invented the first modern running shoe, the New Balance Trackster [1]. Due to interest by runners, New Balance modified its Trackster by increasing the heel height, adding a continuous outsole, and placing a wedge of rubber under the back part of the heel. As the aerobic revolution began in 1968, New Balance extended its grasp on the sports shoe arena and Americans were encouraged to walk away from the couch and start exercising [1]. In response to the need for dual usage, New Balance introduced the Speed Star that was designed to be worn on and off the track.

The Modest Beginnings of the Nike Shoe Empire

University of Oregon track coach, Bill Bowerman, knew what he wanted in a running shoe, and he even created shoes for his track team members because his understanding of running form and shoe construction presented higher standards than those set by the current market. In 1964, Bowerman joined forces with one of his ex-athletes, Phil Knight, and began a small shoe company called Blue Ribbon Sports that made a line of shoes with the Tiger shoe company in Japan [3]. Bowerman and Knight were extremely busy, so through the extra efforts of Jeff Johnson, a former collegiate runner at Stanford, the Tiger Marathon and Roadrunner became the most popular running shoes on the market in 1967 [1]. The Tiger Marathon had a light rubber outsole with a separate heel and forepart, including a reverse leather upper. In 1967, they continued to modify the running world as they offered all nylon uppers. Johnson created the idea of a continuous midsole by removing the outsole of the Tiger shoe and replacing it with a shower slipper with an outer layer of rubber.

In 1972, Tiger and Blue Ribbon Sports separated over distribution disputes [1]. Fortunately, the American following of Bowerman and Knight's did not falter with the disintegration of this partnership. With the addition of a "swoosh" logo from one of Knight's students at Portland State College and the appropriate naming of Nike for the winged, Greek goddess of victory from Jeff Johnson's dream, this fresh company was able to continue production by establishing a deal with one of Tiger's competitors [1, 3]. Further changes in their shoes occurred as Bowerman and a colleague, Jeff Holister, used urethane and a waffle iron to construct extremely light running shoes [1]. Since its conception, the Nike Company has dominated the shoe world and continues to strive for perfection.

Breakthrough by Brooks

The Brooks Company began in 1914 by making ice skates and cleated shoes. During the running craze in the 1970s, the company flourished in the running shoe market. In 1974, Jerry Tuner called a chemical engineer who introduced the light, shock-absorbing material of ethylene vinyl acetate, more commonly known as EVA, to anxious customers [1].

For decades, running shoe companies have been dueling to make a better shoe and perhaps a bigger profit, but it wasn't until podiatrists and researches became involved that shoes were able to evolve once more to deliver maximum performance.

Key Contributors in Athletic Shoe Development

The athletic shoe market in America is a huge industry. Early on, shoes were an extremely basic item. With the emergence of competitive sports, shoes became more high-tech, and added many more features. Podiatrists became involved in the designing of shoes in the 1970s. They provided ways to reduce injuries and enhance performance of athletes through modifications of shoes [4]. Here we will feature ten people who jump-started the evolution of the modern athletic shoe and their contributions to the field of shoe designing.

Bill Bowerman was most noted for as the track coach for the University of Oregon. Initially, he came to Oregon to study and play football. As he saw his first track meet, he decided he wanted to run [1]. After school, Bowerman coached football and basketball for a few years, but starting in 1949, he began a productive 24 year venture of coaching track and field. He coached many Olympians, All-Americans, and other world-class runners [5].

Making shoes for his runners was his main area of contribution. One of Bowerman's focuses was to reduce the weight of the shoe in order to allow the runner to use less energy and to reduce blisters [5]. He would do this by taking a standard last and shaving it down to fit a specific foot type. Through his intelligent coaching and expertise in custom shoe making, runners soon topped the list of the nation's best athletes. One of Bowerman's runners was Phil Knight [1].

Phil Knight approached Bowerman and proposed to him a partnership in a running shoe business. This company became known as Blue Ribbon Sports. Bowerman was the designer of the shoes as Knight was the businessman. They joined Onitsuka Tiger in Japan, who made their shoes. Then they split from Tiger and became known as Nike, one of the leading running shoe companies today. One day, Bowerman used his wife's waffle iron on the sole of a shoe. Today, this waffle design is very common in the outsoles of running shoes [1].

Now, Bill Bowerman is a member of the National Distance Running Hall of Fame, the USA Track and Field Hall of Fame, the Oregon Sports Hall of Fame, and Oregon's Athletic Hall of Fame, but his contributions to shoe making has left the biggest mark in this world today [6].

Phil Knight was another prosperous product of Oregon. As a kid, he loved to run. He was part of Bill Bowerman's team at University of Oregon. He was not the best runner on the team, so he was one of the athletes to consistently test the shoes Bowerman designed.

After college, Knight enrolled at the Graduate School of Business at Stanford. Knowing that the more expensive German shoes were more comfortable than the cheap Japanese shoes, Knight wrote a paper for a class project on "Can Japanese Sports Shoes Do to German Sports Shoes What Japanese Cameras Did to German Cameras?". He designed a better, less-expensive shoe than the Germans [3].

Knight then visited Japan and went to the Onitsuka shoe factory. He was astonished by how good the quality was and how inexpensive the shoes were. Knight made a deal with Onitsuka and began to distribute the Tigers in the United States. He partnered with his former coach, Bill Bowerman, who became the designer of the shoes for their business. Their company then split from Onitsuka in 1972. As Knight was thinking of a new name for the company, Jeff Johnson came up with the name Nike, after the winged goddess of victory. Johnson became the marketer of the business [3].

Phil Knight is now in the Oregon Sports Hall of Fame [7]. A simple graduate school project eventually led him to develop one of the biggest running shoe companies in the world known to produce quality shoes.

Steve Subotnick, D.P.M., D.C., is a podiatrist who has been practicing in northern California since 1971. In addition to sports biomechanics and medicine, he also has a background in naturopathy, homeopathy, chiropractic, and foot and ankle surgery [8]. He is one of the founders and past presidents of the American Academy of Podiatric Sports Medicine and a past Fellow of the American College of Sports Medicine. Dr. Subotnick has written three paperback books and three medical text books on sports medicine.

In 1976, Subotnick gave the Brooks Shoe Company advice on an innovation to their running shoes. Dr. Subotnick strongly believed in the use of sport-specific biomechanics for shoe design, and he suggested the use of a varus wedge because of the functional varus inherent in running [4]. This design raised the inside of the heel compared to the outside by incorporating a four degree angle into the midsole. It is used to bring the subtalar joint into a neutral position during unidirectional running. With this innovation came the Brooks Vantage, which was a top-rated shoe at the time for 5 years. The varus wedge evolved into variable durometer midsoles with reinforced counters to help decrease excessive pronation [1].

Through his expertise in running shoes and sports biomechanics and kinesiology, Subotnick became an Olympic team podiatrist and an NBA team podiatrist for the Golden State Warriors.

Harry Hlavac, D.P.M., Ed.D., is a podiatrist who recently retired after practicing in California for over 35 years. He is one of the founders and past presidents of the American Academy of Podiatric Sports Medicine. He founded a foot care company, developed the Hlavac Strap, and wrote a book on sports medicine advice for athletes [9].

In the 1980s, Hlavac worked with Nike on a modification for their shoes, which resulted in the use of the cobra pad in one of its popular shoes, the Equator [4].

Rob Roy McGregor, D.P.M., is a podiatrist who practiced in Massachusetts for over 50 years. He focused mainly on diabetic feet until he helped with the Boston Marathon. After this marathon, McGregor began to devote his practice mainly to runners [1].

In the 1970s, Dr. McGregor worked with Etonic shoes [4]. He designed a "one-piece heel and arch support." This became known as the Dynamic Heel Cradle. The Dynamic Heel Cradle is a compressible insert in the shoe that has a heel cup all around the rear foot and gives support to the arch by thickening in the inside arch [1].

McGregor's design was one of the first items to hit the market that was designed by a podiatrist [1]. It would be safe to say he was one of the podiatrists to kick-start the evolution of the running shoe.

Lloyd Smith, D.P.M., is a podiatrist who has been practicing in Massachusetts for many years. He is a former president of the American Podiatric Medical Association. Smith has been working with runners and shoes for a long time. Dr. Smith, along with Drs. Dianne English and John McGillicuddy, obtained histories and diagnoses on almost a 1000 runners. They also looked at whether the number injuries changed within a decade [1].

Smith eventually worked with New Balance and also obtained a few patents of his own. One patent involved an external counter and cushion assembly for an athletic shoe. This is used to control pronation while still providing comfort through the increased cushioning and wedge in the midsole [10]. Another patent was an internal dynamic rocker element in casual or athletic shoes. This is a rocker element placed at the forefoot end of the midsole to provide comfort [11].

Dr. Smith continues to practice and devotes much of his practice to sports injuries and shoes [12].

Barry Bates, Ph.D., was the director of biomechanics at the University of Oregon for 25 years. The focus of his research was mainly on lower extremity function of runners [13]. In the mid-1970s, Bates, along with Drs. Stan James and Louis Osternig, gathered and presented data on injuries to runners. They wrote the epic paper on the biomechanics of running. This was the first time this type of data was presented based upon a physical examination of the runner [1].

Bates determined that shoes in extreme temperatures lose their stability. In the 1990s, Bates worked with Asics and invented a shoe comprising a liquid cushioning element [14]. He felt that shoes with this component were less affected by extremely hot temperatures [15]. This was known as the Asics gel.

Dr. Bates is very well known for his concept of running backwards. He states that backward running helps with muscle balance and injury prevention among many other things. Bates also says that backward running has rehabilitation benefits. These include rehabilitation from Achilles' tendon injuries and ankle sprains [16].

Peter Cavanaugh, Ph.D., was an Associate Professor of Biomechanics at The Pennsylvania State University. His main area of research is in locomotion and footwear studies. Cavanaugh is the author of *The Running Shoe Book* and *Physiology and Biomechanics of Cycling*, which is by far the best book written on the history and development of running shoes [1].

Cavanaugh worked with Puma and produced footwear having an adjustable width, foot form, and cushioning. This is done by varying the material of the midsole [17]. He performed a study showing that running shoes help relieve plantar pressure in diabetics. The basis of Cavanaugh's studies has been that shoes aid in shock absorption and stability. These contribute to motion control which prevents injury [18].

Benno Nigg, Ph.D., is the director of the human performance lab at the University of Calgary. Prior to Calgary he was in Zurich. He focuses his research on human locomotion, including mobility and longevity, as well as products related to movement, such as shoes and orthoses. Dr. Nigg has over 290 publications and has written/edited ten books [19].

Nigg states that shoes should be an "additional shell of skin around the foot, allowing the foot to do what it does naturally." As a result of a study he conducted on ski boots, he found ski boots are the opposite of running shoes since they "anchor the foot in a block." Running shoes allow for controlled motion, whereas ski boots stabilize the foot and ankle, allowing for only a forward bend at the ankle, while transferring pressure from the ankle and foot to the ski edges [20].

Throughout the hundreds of Nigg's studies and contributions, the one he is most known for is his work with Adidas. Adidas came to his lab and asked to create a soccer shoe for David Beckham. The result of this was the Adidas Predator Pulse. Dr. Gerald Cole describes, "Dr. Nigg is one of the pioneers of footwear biomechanics research" [21].

Howard Dannenberg, D.P.M., is a podiatrist who practiced in New Hampshire for many years. He made huge contributions to the world of high heels and running shoes. For high-heeled shoes, he developed the Insolia shoe insert to aid in the back pain and sagittal plane dysfunction of these patients [22].

Dannenberg is the inventor of the Kinetic Wedge, which provided comfort to running shoes. He introduced this product to the Brooks Shoe Company [4]. The Kinetic Wedge formed the foundation of the very successful Brooks shoes.

Athletic Shoe Early Research

In the early 1970s, there was limited research and development being done in running and athletic shoes. Addidas was doing work with Benno Nigg, Ph.D., on various projects, and his lab also did research and development on ski boots. Phil Knight, in the early days, consulted with Hlavac and Subotnick. Subotnick glued the waffle outsoles from Bowerman–to the outside of runninf shoes with a glue gun–only to have these out soles fall off during long trail runs in Hayward CA, Hills–were he then lived with his you family of three children. Personal experience recalls gluing Coach Bowerman's waffle outsoles, which he actually made in a waffle iron, to the bottom of running shoes using a glue gun, then going for long runs in the Hayward hills, only to have the outsoles fall off. Later Nike was to develop a sophisticated research and development center.

Shortly thereafter, Jerry Turner from Brooks consulted me to help develop an improved running shoe. Peter Cavanagh, Ph.D., did research for Puma. Various others did research and consulting with different shoe companies. At one time the Rockport had a podiatry advisory board.

The American Academy of Podiatric Sports Medicine (the Academy), under the guidance of Tom Sgarlato, D.P.M., Robert Barnes, D.P.M., and Dick Gilbert, D.P.M., was formed in the early 1970s. The Academy, in conjunction with the college, had large, multidisciplinary sport medicine seminars under the direction of Dr.Subotnick who at that time was director of Graduate Education at the California College of Podiatric Medicine, and invited the directors of the major university biomechanics laboratories. Peter Cavanagh, Ph.D., Benno Nigg, Ph.D., and Barry Bates, Ph.D., were among the early participants. These "real scientists" took rather primitive research back to their respective labs and elevated the research to much higher levels.

Early work with other podiatrists such as John Pagliano, D.P.M., was based on the observation that runners running on a crowned road had supination of one foot with pronation of the other. The pronated foot resulted in a functional valgus at the knee with lateral mal tracking of the patella. Runners on level surfaces had a functional varus due to the narrow base of gait in runners. The pronated foot had one set of lower extremity problems while the supinated foot had others. By controlling foot function, with shoe design, foot orthotics, and training technique, the entire lower extremity from the toes to the low back could be affected.

Subotnick preformed reseach with the aid of? High-speed motion pictures of runners with various types of shoe and orthotic modifications verified our early observations. Stress plate research and research with electromyography using telemetry was performed to observe the effect that foot function had on muscle fiber recruitment and muscle phasic activity. This early research supported the thought that a myriad of running-related problems could be prevented and treated by attempting to alter foot function. This was the early premises of Podiatric sports medicine—sports podiatry and the biomechanics Ph.D.'s took this premises and proved its validity with sophisticated research that far exceeded early attempts. As an Podiatric Sports Medicine Academy, the first fledging members planted a seed that forever changed the development of athletic shoes and the diagnoses, prevention, and treatment of running injuries. The Academy also became involved in the prevention and treatment of various types of sports injuries ranging from skiing, soccer, football, basketball, hockey, baseball, tennis, to golf and virtually all sports, even bowling.

Sports podiatrists joined the medical teams for high school, college, and professional sports, and a few became members of the Olympic medical team and worked at the various Olympic training centers with the sports physiologists, orthopedists, trainers, and biomechanics researchers.

Now most major universities in the United States, Canada, and Europe have biomechanics departments with multiple research projects on-going, many of which are sponsored by various sports shoe companies. The entire field of sport biomechanics and kinesiology has grown and expanded over just a few decades.

Running Shoe Anatomy: Past and Present

Refer to Chap. 5 for a complete discussion of running shoe anatomy; the following discussion will list shoe anatomy, then compare and contrast the evolution of current shoe materials.

It is important for both the athlete and the sports medicine practitioners to have a working knowledge of the anatomy and function of a running or athletic shoe. This understanding can both prevent injury and enhance recovery from injury or any shoe-related problem. An example is the athlete with a "Haglund's disease," which is a retrocalcaneal exostosis and bursitis, or "pump-bump" aggravated by the counter of the shoe digging into the posterior heel and Achilles insertion. Simply removing the counter of the shoe, or changing shoe models or brands, can convert a very painful and disabling condition to a pain-free past memory in short order. In many cases, it's been the difference for Olympic athletes qualifying in the Olympic trials. It is no secret that it is easier to operate on a shoe and the results are consistently better, than operating athletes prematurely.

Basic knowledge of the parts of a running shoe, the anatomy, can be as important as knowledge of functional anatomy when treating an athlete with a shoe-related problem. Being aware of the different options and varieties of material used may help determine the athletic shoe that will best fit not only its purpose but the athlete's feet. *The running shoe is composed of two main parts: the upper and the bottom.* The upper covers the foot and the bottom provides a barrier between the foot and the environment, be it a trail, track, court, field, slope, whatever surface the foot contacts.

The Upper

The *vamp* is the portion of the shoe covering the forefoot. The remainder of the upper covering is referred to as inside and outside quarters. Featherline is where the upper meets the sole of the shoe. Traditionally, the vamp is constructed from one piece of material minimizing the number of seams and therefore irritation to the foot.

The *upper* has several intricate details as there are several attachments that need to be placed on it to complete the running shoe. The upper starts as one large piece, usually nylon. Leather, or synthetic leather-like materials, is added as reinforcement in needed areas. The *eyelet* forms the *throat* of the shoe acting as the anchor for lacing. The *tongue* is a padded piece that lies beneath the lacing to provide cushioning to the top of the foot against the pressure of the laces. The reinforcement sewn on the upper at the level of the arch is to help support the eyelet. *Reinforcement* on the outside is known as *saddle*. Reinforcement on the inside of the upper is known as the *arch bandage*.

Foxing is the suede covering at the back of the shoe. The *toe box* is the front of the upper that has leather overlay known as a *wing tip*. A leather tip that does not meet the throat and covers only the rim of the toes is referred to as a *mudguard tip* or *moccasin toe box*. To make the toe box sturdier, a stiffener can be placed underneath the wing tip.

The padded vinyl or stretch nylon that covers the upper where there is contact of the foot just below the ankle to the shoe is called the *collar*. The *collar* has a projection that comes up above the heel to help protect the Achilles tendon from irritation. The *heel counter* is at the back of the shoe surrounding the heel of the foot. It has a pocket for a stiffener to help control the rear foot during motion. Heel counters are firm and inflexible to prevent excessive motion during running. It helps to hold the foot in place [1]. It also can be a significant source of rubbing and irritation to the posterior heal or Achilles insertion.

Upper Materials: Past and Present

The upper is vital for fit and managing moisture, making the choice of materials important in the construction of the running shoe. Leather has several properties that make it resourceful in shoes. It can permanently change its form to fit the foot, store perspiration, transmit water vapor from the foot to the outer air, withstand tension, and resist abrasion. Yet, leather is not often used alone as the upper. Runners and other athlete's have no limitations when it comes to weather. Rain or shine athletes will be outdoors working out or competing. Under unfavorable weather conditions such as rain, leather becomes plastic, stretching to a different length and not returning to its original size. Leather also takes longer to dry after exposure to water. It is now used as an accessory to reinforce the upper [1].

More recently, uppers are constructed from synthetic fabric with patches of synthetic leather for durability. Synthetic fabrics tend to cover the area from the laces and down the side of the shoe to the sole. This decreases the weight of the running shoe, making the shoe washable and breathable, so the feet don't become too hot. The synthetic materials are better at wicking and heat transfer. Nylon taffeta is a plain weave that is smooth on both sides. It is more resistant to permanent deformation and dries easily after exposure to water. However, shoes made from it do not allow the foot to breathe well because of its tight weave. Making the holes between the strands bigger with less taffeta threads compromises the integrity, causing it to lose its resistance to abrasion. Therefore, nylon mesh which is knitted instead of woven is more popularly used. Its strength doesn't depend on the tightness of the weave [1]. These newer "high technology" materials have greatly improved the function, durability, and comfort of athletic shoes, and the same is true of athletic clothing and gear.

The Bottom

The bottom of the athletic shoe is made up of three main components: midsole, wedge, and outsole.

The *midsole* lies between the upper and both the outsole and wedge. Its purpose is for shock absorption, attenuation, and dampening. The cushioning effect is balanced with the stability function. This is an important and often crucial factor. The more cushioning, the less stability while the softer the midsole materials, the less stability. This makes the midsole one of the most important components of the running shoe. All too often a runner will purchase a new shoe based on that "soft, cushy feel" only to develop excessive pronation and associated injuries that are directly related to the shoe selection.

The *heel wedge* lies between the midsole and the outsole at the rear of the shoe. It helps with both heal impact and shock attenuation and provides a heel lift.

The *outsole* is the layer that contacts the ground. While it also contributes some to shock absorption, its main purpose is durability and traction. It is where the "rubber meets the ground." It can be the difference between life and death in activities such as rock climbing. It helps determine the amount of torsion rigidity and flexibility of a shoe. There is an *insole board* on top of the midsole that is found in most shoes.

The *sock liner* covers the insole board. Different materials for wicking and comfort are used to line the inside of the shoe [1].

Materials: Past and Present

Midsole

The midsole no longer used leather soles because of the poor shock absorption it offered. Natural sheet rubber was included for a little while, but it was heavy and had a minor improvement in absorbing shock. Foam rubber with small bubbles of encapsulated air was lighter and a better shock absorber than sheet rubber. There is a chemical blowing agent that reacts with other chemicals in the mixture under right temperatures to produce gas. The small bubbles of air trapped within the material are known as closed cell foam and appears to be lighter and a better shock absorber than sheet rubber. Closed cell foams absorbed energy because the walls of the air cells deformed to absorb energy, and the small bubbles of air compressed to act as shock absorbers. There was then a movement to use foams from polymers. It reduced the weight and density by a factor of four and improved shock absorption [1].

Today, the most common midsole material now is a type of foam called ethylene vinyl acetate (EVA) [23]. It provides cushioning, increases shock absorption, and decreases shearing. Polyurethane (PU), another form of polymer, resists compression and is more durable than EVA, but is heavier and harder. Some midsoles are made with the combination of both EVA and PU. EVA is placed in the forefoot and PU in the rearfoot. The logic behind this change is that the heel takes on 2–3 times the body weight of a runner; therefore it needs material that is more resistant to compression and can absorb the impact of that force [1]. A dual density midsole is made from materials of two different densities. Multi-density midsoles contain more than two different densities [23]. The purpose of different densities is to accentuate the areas that need more support. Often times, the higher density material is placed on the medial side of the shoe to reduce overpronation. Mixed materials are also used for the midsole [24]. EVA impregnated with solid rubber can improve the resistance to compression and have a quicker rebound [1]. Different manufacturers are finding ways to come up with more cushioning devices such as gel and air in the midsole to maintain cushioning that lasts longer than EVA, but it may come at more of an expense [25].

Wedges

Wedges are also known as medial post. They are designed by tapering the midsole, so the medial side is thicker than the outside border. It was created because feet tend to pronate or roll in beyond the neutral position. The wedge helps reduce overpronation in running and increases stability on the inner part of the shoe [1]. To properly serve its function, wedges are often made from a material with higher density foam or thermal plastic unit to prevent the medial arch from collapsing. Thermal plastic unit creates stiffness in the midsole and makes the shoe lighter [23].

Outsole

Rubber has been the material of choice for the outsole because it is both soft and durable [1]. There are several different types of rubber that can be used. Tire rubber is durable but heavy. Gum rubber offers a good grip [26]. Despite the various options, the outsole is usually made from blown rubber and carbon rubber. Blown rubber is air-injected rubber, making the outsole lighter and softer to provide cushioning and flexibility. However, it wears quickly making it less durable than carbon rubber [23]. Carbon rubber is both light and the most durable type of rubber. With its distinct properties, blown rubber serves better purpose at the forefoot of the shoe and carbon rubber at the heel. Like the midsole, outsoles can also be made from mixing different materials [26].

Motion control shoes help with both the subtalar joint and midtarsal joint, while stability shoes control only the subtalar joint. Therefore the shape and design of the outsole is an important factor in determining what kind of control runners need [26]. The straighter the shoe, the more motion control it offers, so it is usually for those with a pes planus foot type. Slightly and semi-curved outsoles have less motion control and are for those with a more "normal" foot type. Curved outsoles are in neutral shoes, allowing for no motion control, so this type of running shoe is generally for sprinters and can give supinators more cushion [26].

Furthermore, outsole designs help runners maximize the use of their shoes [1]. Stud or waffle outsoles are ideal for running on dirt or grass because it improves traction and stability. Ripple soles are better for running on cement or asphalt [25].

Insole and Sockliner

The insole board is stable and flexible. It should serve as a rigid base for the shoe, but flexible enough to allow the foot some movement once in the shoe. It is made of cellulose fibers. Because the insole is exposed to sweat from the feet, better boards include components to inhibit bacterial and fungal growth from the moisture in the shoe [1].

The sockliner is the layer that lies between the foot and the insole board. Its principle functions are to absorb perspiration, energy absorption, and comfort. Because each foot is shaped differently, good sockliners should conform to match the foot shape. EVA foam is conducive to this. Terrycloth lining works well for wicking away perspiration. Sockliners also need to generate enough friction to prevent the foot from sliding inside the shoe. Blisters on the dorsum of the foot can occur from rubbing with the upper because of too much movement. Velour has also been used as a sockliner because it creates friction [1].

Putting It All Together

The construction of the running shoe to attach the upper to the sole has three options: board lasting, slip lasting, or combination lasting. Board lasting is a fiber board that runs from the heel to the forefoot. Shoes with this type of lasting have the most stability. Slip lasting has no board at all. It provides stability and the most comfort. A combination last has a board at the rearfoot for stability and is slip lasted in the forefoot for flexibility and comfort. Removing the insole and exploring the inside of the shoe can determine which kind of last the running shoe has [1, 26].

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Evolution of Foot Orthoses in Sports

2

Kevin A. Kirby

Introduction

Foot orthoses have been used for well over 200 years by the medical profession for the treatment of various pathologies of the foot and lower extremity [1, 2]. Starting from their simple origins as leather, cork, and/or metallic in-shoe arch supports, foot orthoses have gradually evolved into a complex assortment of in-shoe medical devices that may be fabricated from a multitude of synthetic and natural materials to accomplish the intended therapeutic goals for the injured patient. For the clinician that treats both athletic and nonathletic injuries of the foot and lower extremity, foot orthoses are an invaluable therapeutic tool in the treatment of many painful pathologies of the foot and lower extremity, in the prevention of new injuries in the foot and lower extremity and in the optimization of the biomechanics of the individual during sports and other weight-bearing activities. Because of their therapeutic effectiveness in the treatment of a wide range of painful mechanically based pathologies in the human locomotor apparatus, foot orthoses are often considered by many podiatrists, sports physicians, and foot-care specialists to be one of the most important treatment modalities for these conditions.

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Definition of Foot Orthoses

To the lay public and many medical professionals, foot orthoses are often described by the slang word "orthotics" to describe the wide variety of in-shoe devices ranging from non-custom arch supports to prescription custom-molded foot orthoses. Because of this potentially confusing problem with terminology, this chapter will use the term "foot orthosis" to describe all types of therapeutic in-shoe medical devices that are intended to treat pathologies of the foot and/or lower extremities.

It is appropriate within the context of laying down proper terminology for foot orthoses that a proper definition also be given. Dorland's Medical Dictionary gives a relatively generic definition of an orthosis as being "an orthopedic appliance or apparatus used to support, align, prevent, or correct deformities or to improve the function of movable parts of the body [3]." Wu defined a foot orthosis as "a medical device employed to support and align the foot, to prevent or correct foot deformities, or to improve the functions of the foot [4]." However, it is clear from the prevailing research that will be reviewed in this chapter that foot orthoses have a much more complex function than simply "supporting or aligning the skeleton" or serving to "support and align the foot." Due to the need for a more modern definition of these in-shoe medical devices, especially considering the extensive scientific research that has been performed on foot orthoses within the past few decades, Kirby, in 1998, proposed the following definition for foot orthoses:

> An in-shoe medical device which is designed to alter the magnitudes and temporal patterns of the reaction forces acting on the plantar aspect of the foot in order to allow more normal foot and lower extremity function and to decrease pathologic loading forces on the structural components of the foot and lower extremity during weight-bearing activities [5].

Historical Evolution of Foot Orthoses

Foot orthoses have been used by clinicians for the treatment of foot and lower extremity pathologies for well over two centuries. One of the earliest references to the use of foot orthoses in the medical literature came in 1781 from a Dutch physician, Petrus Camper, who described treating children with flatfoot deformity with arch-supporting in-shoe orthoses [2]. In 1845, Lewis Durlacher, a British chiropodist who was appointed as surgeon-chiropodist for King George IV, King William IV, and Queen Victoria, advocated the use of leather foot orthoses to correct for "plantar pressure lesions" and "foot imbalances" [6]. Other practitioners and bootmakers of Durlacher's era described the use of built-up in-shoe leather devices and the medical literature of the era described foot orthoses as being valuable medical devices for the treatment of painful pathologies and deformities within the foot and lower extremity [1, 7]. The medical literature of the late nineteenth century and early twentieth century also describes the efforts of pioneering podiatrists and medical doctors, such as Whitman [8, 9], Roberts [10], Schuster [1], Morton [11], Levy [12], and Helfet [13], to create more effective foot orthoses for the treatment of mechanically based foot pathologies.

Even though foot orthoses were being used by many medical practitioners in the first half of the twentieth century, it was not until 1958 that the era of modern foot orthosis therapy began. It was at this time, when a California podiatrist, Merton Root, began to fabricate thermoplastic foot orthoses made around feet casted in a subtalar joint (STJ) rotational position [which he coined as the "neutral position" in 1954] that the era of modern prescription foot orthoses was born [14–18]. The introduction by Root and coworkers of a new lower extremity biomechanical classification system based on the STJ neutral position and of eight "biophysical criteria for normalcy" of the foot and lower extremity that were supposedly required to be present in the foot and lower extremity before it could be considered ideal, or "normal," served as the biomechanical basis for many clinicians involved in foot orthosis therapy since the mid-1960s [19]. Later refinements and modifications to the modern foot orthosis made by Henderson and Campbell [20], Blake [21–23], Kirby [5, 24, 25], and others [26] have added significantly to the potential therapeutic effectiveness and range of pathologies that may be treated with foot orthoses.

Research and Theory on Orthosis Function

The early medical literature on foot orthoses, even though it was probably quite valuable for the clinician of that era, unfortunately consisted of only a few anecdotal accounts from interested practitioners regarding the therapeutic effectiveness of foot orthoses on their own patients. However, in today's medical environment, which demands more evidence-based research to inform the clinician of the most effective medical therapy to choose for their patients, anecdotal reports of a single clinician's results with foot orthoses is no longer considered to be evidence of high value [27]. Fortunately, due to the numerous computer-based technological advances that have occurred over the past few decades, both clinical specialists and researchers within the international biomechanics community have been able to more effectively combine their efforts to produce a virtual explosion in foot orthosis research [28]. The effective synergistic collaboration between clinician and researcher [29, 30] has enabled the medical specialties to progress toward better scientific validation of the observations that clinicians have been claiming for over two centuries in the successful treatment of their injured athletes and nonathletes with foot orthoses.

Research on Therapeutic Effectiveness of Orthoses

Numerous research studies have now provided for solid validation of the therapeutic effectiveness of the treatment of injuries within both the athletic and nonathletic population. In the recreational and competitive runner, the success rate at treating various foot and lower extremity injuries has been reported as being between 50 and 90% [31–34]. A complete resolution or significant improvement in symptoms was found in the foot orthosis treatment of injuries in 76% of 500 distance runners [35]. In 180 patients with athletic injuries, 70% of the athletes reported that foot orthoses "definitely helped" their injuries [21]. In addition, 76.5% of patients improved and 2% were asymptomatic after 2–4 weeks of receiving the custom foot orthoses in a study of 102 athletic patients with patellofemoral pain syndrome [36].

Further evidence of the therapeutic effects of foot orthoses comes from the research literature on treatment of nonathletic injuries. In a study of 81 patients treated with foot orthoses, 91% were "satisfied" and 52% "wouldn't leave home without them" [37]. In a study of 520 patients treated with foot orthoses, 83% were satisfied and 95% reported their problem had either partially or completely resolved with their orthoses [38]. The majority of the 275 patients that had worn custom foot orthoses for over a year had between 60 and 100% relief of symptoms with only 9% reporting no relief of symptoms [39]. In a prospective study of 79 women over the age of 65, the group of subjects that received custom foot orthoses and was given guidance on shoe fitting had significant improvements in mental health, bodily pain, and general health compared to their non-orthosis wearing controls so that foot orthosis intervention was determined to be "markedly effective not only in the physical but also in the mental aspect" [40].

Recent prospective scientific studies have yielded very positive results indicating the potential for foot orthoses to not only successfully treat injuries but also to prevent injuries in athletic individuals. In a large scale prospective study by Franklyn-Miller and colleagues at the Britannia Royal Naval College in the United Kingdom, 400 military officer trainees were divided into an orthosis group ($n = 200$) and a no-orthosis group ($n = 200$) and were followed over a 7 week period of basic training. The number of injuries in the no-orthosis group was 61, while the number of injuries in the orthosis group was only 21 over the 7 week period, representing a very significant injury risk reduction for foot orthoses ($p < 0.0001$). In their study, Frankly-Miller and colleagues also found a tenfold reduction in medial tibial stress syndrome and a sevenfold reduction in the rate of chronic exertional compartment syndrome in the recruits that wore foot orthoses during basic training [41].

In another prospective study of infantry recruits, those recruits wearing foot orthoses had an 11.3–16.3% reduction in incidence of stress fractures than in the non-orthotic control group [42]. Yet another prospective study in military recruits found that foot orthoses reduced the incidence of femoral stress fractures in those recruits with pes cavus deformity and reduced the incidence of metatarsal fractures in those recruits with pes planus deformity [43].

A very recent prospective double-blind randomized clinical trial that compared custom foot orthoses to prefabricated foot orthoses and sham insoles in 77 patients with plantar fasciitis symptoms demonstrated that the custom foot orthosis group had a fivefold greater improvement in spontaneous physical activity versus the prefabricated insole and sham insole groups [44]. In another study on the orthosis treatment of plantar fasciitis, a 75% reduction in disability rating and a 66% reduction in pain rating were found when patients wore custom foot orthoses [45].

A recent study of 179 subjects with patellofemoral syndrome of over 6 weeks duration treated either with foot orthoses or with physiotherapy and flat insoles shows that foot orthoses produced a significant improvement in treatment success (85%) versus the flat insoles (58%) [46]. In a study of 20 female adolescent subjects with patellofemoral syndrome, foot orthoses were found to significantly improve symptoms versus muscle strengthening alone [47]. Also, in a recent study of 52 subjects with patellofemoral syndrome, foot orthoses produced significant improvements in pain, and the ability of subjects to perform single-leg squats, step downs, and single-leg rises from sitting [48]. Another study on 40 subjects with anterior knee pain of at least 6 weeks duration were treated either with foot orthoses or with no treatment and found that the orthoses produced significant improvements in both symptoms and function ($p = 0.008$) versus the "wait and see" approach [49].

In research on 64 subjects with osteoarthritis in the foot and ankle, 100% of the patients wearing orthoses had significantly longer relief of pain than those patients receiving only nonsteroidal anti-inflammatory drugs [50]. Further support for the mechanical potential for foot orthoses to decrease the internal loading forces on the foot and lower extremity comes from a recent study of 42 patients with mechanical midfoot pain and bone marrow lesions on MRI that showed that foot orthoses reduced the bone marrow lesions by 26%, compared to the only 4% reduction in bone marrow lesions in the sham insole group [51].

In certain other medical conditions, foot orthoses have also been found to be therapeutic. In 16 subjects with hemophilia A treated over a 6 week period with foot orthoses, there was found to be significant control of ankle bleeds, decreased pain, decreased disability, and increased activity [52]. Significant improvement in pain and a decrease in foot disability also occurred in patients with rheumatoid arthritis (RA) when they wore custom foot orthoses [53–55]. In addition, in a recent randomized control trial of 40 children with juvenile idiopathic arthritis, it was found that the children wearing custom foot orthoses had significantly greater improvements in overall pain, speed of ambulation, foot pain, and level of disability when compared to those that received shoe inserts or shoes alone [56]. Custom foot orthoses were also found to significantly improve the pain and quality of life in 60 children with juvenile idiopathic arthritis over a 6 month period of treatment [57].

Plantar forefoot pain, or metatarsalgia, has likewise been found to be effectively treated with foot orthoses. In a prospective of 151 subjects with pes cavus deformity, when the subjects wore custom orthoses for 3 months, they showed significant decreases in foot pain, increases in quality of life, and three times more reduction in the magnitude of forefoot plantar pressure when compared to when they wore sham insoles [58]. Plantar forefoot pain, including the force impulse and peak pressure at the metatarsal heads, was found to be significantly reduced in 42 subjects with metatarsalgia that received custom foot orthoses [59]. In addition, multiple studies have noted the significant effect that foot orthoses can have to reduce the magnitude of plantar pressures and aid in the healing of diabetic neuropathic ulcers [60–64].

Recently, the treatment of medial knee osteoarthritis (OA) with customized foot orthoses has also received considerable attention within the research literature. In a prospective study of 156 subjects treated with medial knee OA, there was a significant decrease in nonsteroidal anti-inflammatory drug usage in the subjects that wore foot orthoses [65]. In 30 subjects with medial knee OA treated with foot orthoses, there was significant reduction in knee pain after using foot orthoses at both the 3-week and 9-week assessment periods [66]. Multiple scientific studies have shown that the valgus-wedged foot orthoses used to treat medial knee OA cause a reduction in the magnitude of external knee adduction moment during gait [67–76].

Research has shown that valgus-wedged orthoses causes a lateral shift in the center of pressure (CoP) acting on the plantar foot, which mechanically correlates with a reduction in the external knee adduction moment [77–79]. There are numerous recent studies that have confirmed the positive changes in knee mechanics and knee symptoms that can occur with appropriate application of various types and degrees of valgus-wedged foot orthoses [80–83]. A review of the literature regarding the treatment of medial compartment knee osteoarthritis with laterally wedged foot orthoses led researchers to conclude that their "data indicate a strong scientific basis for applying wedged insoles in attempts to reduce osteoarthritic pain of biomechanical origin" [84].

Another recent focus of attention within foot orthosis research has been on balance and a prevention of falls in the elderly. Postural medial-lateral sway and CoP length and velocity was noted to decrease in multiple studies on the effects of foot orthoses during balance during unipedal and bipedal standing [85–87]. In 13 subjects over 65 years old with a history of poor balance and falls, it was found that all balance tests were improved with the use of foot orthoses [88]. In addition, in a study of 94 elderly women with osteoporosis that were assigned to two groups, one group that received orthoses and the other group not treated with orthoses, the group treated with orthoses showed significant improvements in balance and reductions in pain and disability versus the no-orthosis group [89].

In this extensive review of the research literature on foot orthoses over the past four decades, it is clear that foot orthoses have the potential ability to relieve the symptoms from many painful and disabling foot and lower extremity pathologies, prevent new injuries from occurring and improve balance. These facts, combined with the author's personal experience of treating over 18,000 patients within the past 30 years with custom foot orthoses, make it very clear that foot orthoses can offer significant therapeutic benefit to both athletic and nonathletic patients.

Theories of Foot Orthosis Function

Even though the therapeutic efficacy of foot orthoses has been well documented within the medical literature for the past quarter century, the biomechanical explanation for the impressive therapeutic effects of foot orthoses has been a matter of speculation for well over a century. In 1888, Whitman made a metal foot brace that worked on the theory that the foot could be pushed into proper position either by force or by pain with the use of hard medial and lateral flanges that would rock into inversion once the patient had stepped on it [8]. Morton, in 1935, believed that a "hypermobile first metatarsal segment" was the cause of many foot maladies and that his "compensating insole" with an extension plantar to the first metatarsophalangeal joint would relieve "concentration of stresses on the second metatarsal segment" [11]. Even though early authors claimed excellent clinical results with foot orthoses [13, 90, 91], none offered coherent mechanical theories that described how foot orthoses might accomplish their impressive therapeutic results.

In the late 1950s and early 1960s, Root and his coworkers from the California College of Podiatric Medicine in San Francisco developed a classification system based on an ideal or "normal" structure of the foot and lower extremity that used Root's concept of the STJ neutral position as a reference position for the foot [14, 15, 19, 92, 93]. Root and coworkers integrated their ideas of "normal" structure into an orthosis prescription protocol that had the following goals: (1) to cause the STJ to function around the neutral position, (2) to prevent compensation, or abnormal motions, for foot and lower extremity deformities, and (3) to "lock the midtarsal joint" [94].

New ideas on foot and foot orthosis function came in 1987 when Kirby first proposed that abnormal STJ rotational forces (i.e., moments) were responsible for many mechanically based pathologies in the foot and lower extremity and that abnormal spatial location of the STJ axis was the primary cause of these pathological STJ moments [95]. These ideas were based on the development of the plantar palpation technique for locating the STJ axis [95], a technique which has recently been found to be both reliable and valid within the scientific literature [96, 97].

A foot with a medially deviated STJ axis was suggested to be more likely to suffer from pronation-related symptoms since ground reaction force (GRF) would cause increased magnitudes of external STJ pronation moments (Figs. 2.1 and 2.2). A foot with a laterally deviated STJ axis would tend to suffer from supination-related symptoms since GRF would cause increased magnitudes of external STJ supination moments [95]. Kirby proposed that medial and lateral deviation of the STJ axis caused abnormal changes in the magnitudes of internal STJ moments that are produced by contractile activity of the extrinsic muscles of the foot [95, 99] (Fig. 2.3). When STJ axis spatial location was combined with the mechanical concept of rotational equilibrium, a new theory of foot function, the "Subtalar Joint Axis Location and Rotational Equilibrium (SALRE) Theory of Foot Function," emerged to offer a coherent explanation for the biomechanical cause of many mechanically based pathologies of the foot and lower extremity [95, 98, 99].

In 1992, Kirby and Green first proposed that foot orthoses functioned by altering the external STJ moments that were created by the mechanical actions of ground reaction force (GRF) acting on the plantar foot during weight-bearing activities [93]. They hypothesized that foot orthoses were able to exert their ability to "control pronation" by converting GRF acting lateral to the STJ axis into a more medially located orthosis reaction force (ORF) that would be able to generate increased external STJ supination moments during weight-bearing activities. Using the example of a foot orthosis with a deep inverted heel cup, known as the Blake Inverted Orthosis [21–23, 100], they proposed that the inverted heel cup orthosis produced its impressive clinical results in relieving pronation-related symptoms by increasing the ORF on the medial aspect of the plantar heel so that increased external STJ supination moments would result [93].

Kirby later introduced a foot orthosis modification called the *medial heel skive technique* (Fig. 2.4) that also produced an inverted heel cup in the orthosis, shifted the ORF medially on the plantar heel, and, as a result, increased the external STJ supination moment to more effectively treat difficult pathologies such as pediatric flatfoot deformity, posterior tibial tendon dysfunction, and sinus tarsi syndrome [24].

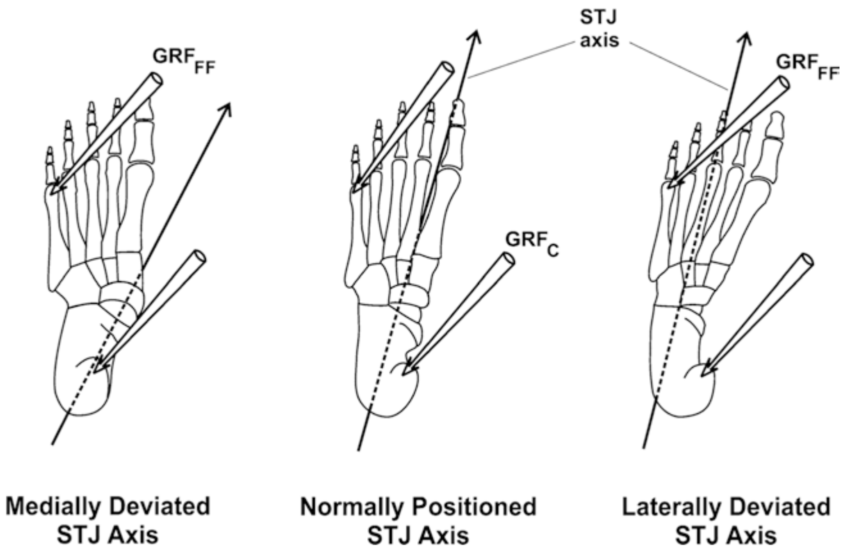

Fig. 2.1 In a foot with a normally positioned subtalar joint (STJ) axis (*center*), the ground reaction force plantar to the calcaneus (GRF_C), will cause a STJ supination moment since it acts medial to the STJ axis. Ground reaction force acting plantar to the fifth metatarsal head (GRF_{FF}) will cause a STJ pronation moment since it acts lateral to the STJ axis. In a foot with a medially deviated STJ axis (*left*), since the plantar calcaneus now has a decreased STJ supination moment arm when compared to normal, GRF_C will cause a decreased magnitude of STJ supination moment. Since the fifth metatarsal head has an increased STJ pronation moment arm, GRF_{FF} will cause an increased magnitude of STJ pronation moment when compared to normal. However, in a foot with a laterally deviated STJ axis (*right*), since the plantar calcaneus now has an increased STJ supination moment arm, GRF_C will cause an increased magnitude of STJ supination moment, and since the fifth metatarsal head has a decreased STJ pronation moment arm, GRF_{FF} will cause a decreased magnitude of STJ pronation moment when compared to normal. Therefore, the net result of the mechanical actions of ground reaction force on a foot with a medial deviated STJ axis is to cause increased magnitude of STJ pronation moment, and the net mechanical result of a laterally deviated STJ axis is to cause increased magnitude of STJ supination moment. (Reprinted with permission from Kirby KA: Subtalar joint axis location and rotational equilibrium theory of foot function. JAPMA, 91:465–488, 2001)

The proposed mechanical effect of the medial heel skive modification of shifting the ORF medially on the plantar aspect of the heel of the foot has been supported by recent research by Bonanno et al. [101]. Other similar inverted heel cup modifications to foot orthoses have been introduced since the introduction of the medial heel skive technique which likely mechanically act in a similar manner to the medial heel skive modification [102–104].

Foot and lower extremity pathologies caused by excessive magnitudes of external STJ supination moment, such as chronic peroneal tendinopathy and chronic inversion ankle sprains, were also proposed to be caused by the interaction of GRF acting on the foot with an abnormally laterally deviated STJ axis [5, 25, 98, 99]. It was suggested that the abnormal STJ supination moments would be best treated with an increased valgus construction within the foot orthosis, including the

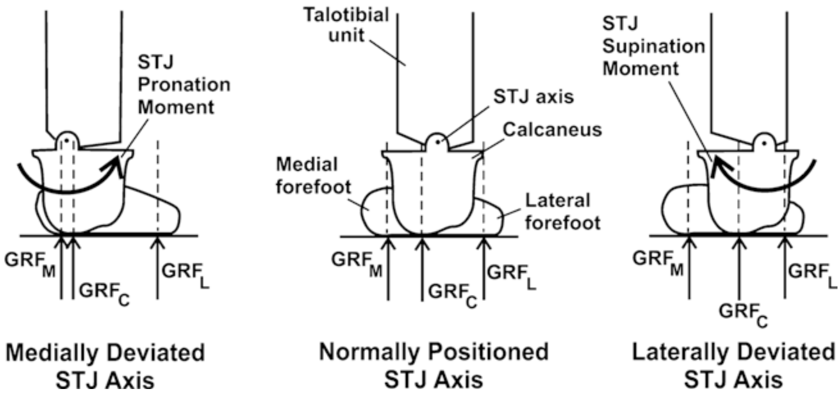

Fig. 2.2 In the model above, a posterior view of the right foot and ankle are modeled as consisting of the talus and tibia combined together to form the talotibial unit which articulates with the foot at the subtalar joint (STJ) axis. The external forces acting on the foot include ground reaction force (GRF) plantar to the calcaneus (GRF_C), GRF plantar to the medial forefoot (GRF_M), and GRF plantar to the lateral forefoot (GRF_L). In a foot with a normal STJ axis location (*center*), the more central location of the STJ axis relative to the structures of plantar foot allows GRF_C, GRF_M, and GRF_L to cause a balancing of STJ supination and STJ pronation moments so that more normal foot function occurs. In a foot with a medially deviated STJ axis (*left*), the more medial location of the STJ axis relative to the plantar structures of the foot will cause a relative lateral shift in GRF_C, GRF_M, and GRF_L, increasing the magnitude of STJ pronation moment and causing more pronation-related symptoms during weight-bearing activities. In a foot with a laterally deviated STJ axis (*right*), the more lateral location of the STJ axis relative to the plantar structures of the foot will cause a relative medial shift in GRF_C, GRF_M, and GRF_L, increasing the magnitude of STJ supination moment and causing more supination-related symptoms

addition of the *lateral heel skive technique* [105] within the heel cup of the orthosis. In this fashion, the orthosis would mechanically increase the magnitude of external STJ pronation moments by shifting ORF more laterally on the plantar foot to more effectively treat supination-related symptoms and pathologies.

In the late 1980s and 1990s, a number of other authors likewise started focusing on the idea that orthosis treatment should not be determined by the results of measuring “deformities” of the foot and lower extremity, as proposed by Root and coworkers, but rather should be determined by the location and nature of the internal loading forces and internal stresses acting on and within injured structures of the patient. The idea that pathological internal loading forces acting on the foot and lower extremity in sports and other weight-bearing activities may be effectively modeled to develop better treatment strategies was pioneered by Benno Nigg and coworkers at the University of Calgary, Canada. Nigg and coworkers realized that since invasive internal measurements could not be made on patients to determine the absolute magnitudes of internal loading forces, reliable estimates of these forces could instead be made with more effective models of the foot and lower extremity [106–108].

However, it was not until 1995, when McPoil and Hunt first coined the term “Tissue Stress Model” that one of the most recent foot orthosis treatment models was given a proper name. McPoil and Hunt suggested that foot orthosis therapy

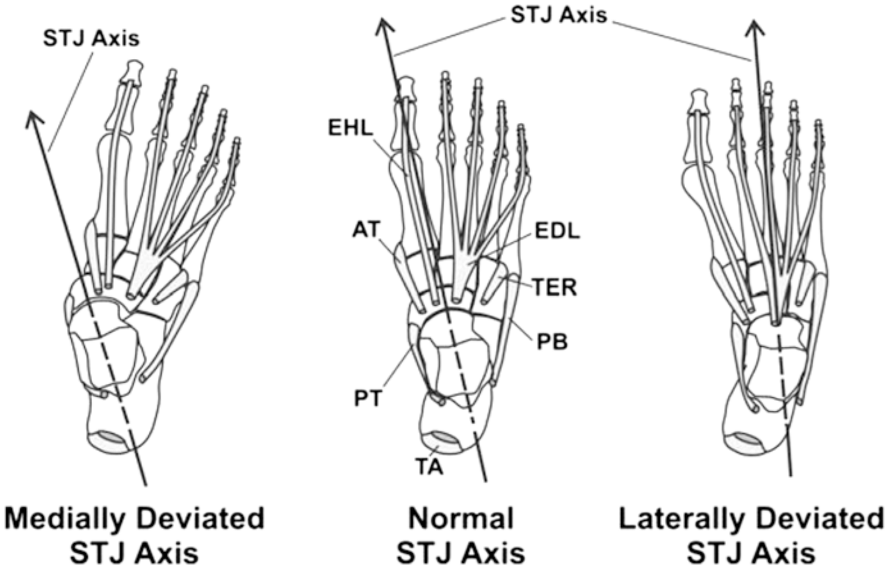

Fig. 2.3 In a foot with a normal STJ axis location (*center*), the posterior tibial (PT), anterior tibial (AT), extensor hallucis longus (EHL), and Achilles tendons (TA) will all cause a STJ supination moment when they exert tensile force on their osseous insertion points since they all insert medial to the STJ axis. However, the extensor digitorum longus (EDL), peroneus tertius (TER), and peroneus brevis (PB) tendons will all cause a STJ pronation moment when they exert tensile force on their insertion points since they all insert lateral to the STJ axis. However, in a foot with a medially deviated STJ axis (*left*), since the muscle tendons located medial to the STJ axis have a reduced STJ supination moment arm, their contractile activity will cause a decreased magnitude of STJ supination moment when compared to normal. In addition, since the muscle tendons lateral to the STJ axis have an increased STJ pronation moment arm, their contractile activity will cause an increased magnitude of STJ pronation moment. In addition, in a foot with a laterally deviated STJ axis (*right*), since the muscle tendons medial to the STJ axis have an increased STJ supination moment arm, their contractile activity will cause an increased magnitude of STJ supination moment when compared to normal. Since the muscle tendons lateral to the STJ axis have a decreased STJ pronation moment arm, their contractile activity will cause a decreased magnitude of STJ pronation moment. Therefore, the net mechanical effect of medial deviation of the STJ axis on the actions of the extrinsic muscles of the foot is to cause increased magnitudes of STJ pronation moment and the net mechanical effect of lateral deviation of the STJ axis on the actions of the extrinsic muscles of the foot is to cause increased magnitudes of STJ supination moment

should be directed toward reducing abnormal levels of tissue stress in order to more effectively design mechanical treatment aimed at healing musculoskeletal injuries caused by pathological internal stress acting on and within the structural components of the foot and lower extremity. They felt that by focusing the clinician's attention on the abnormal stresses causing the injury, rather than on measuring "deformities" of the lower extremity, that optimal mechanical foot therapy could be better achieved [109].

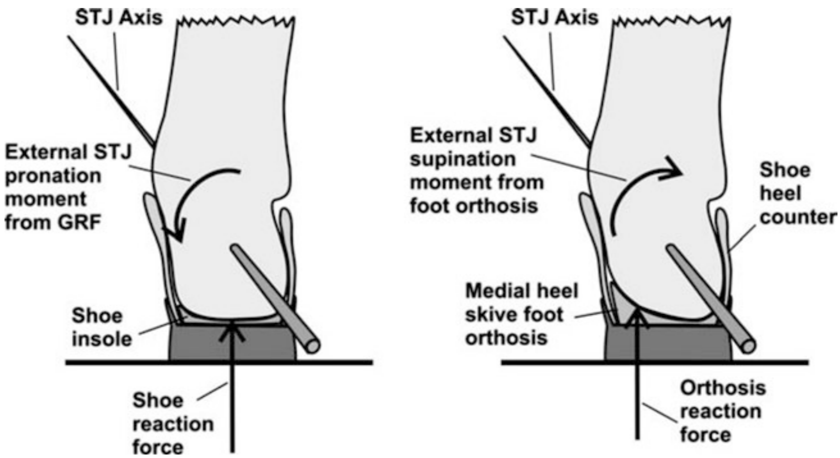

Fig. 2.4 In the illustrations above, the posterior aspect of the right foot with a medially deviated subtalar joint (STJ) axis is shown in a shoe without an orthosis (*left*) and also is shown in a shoe with a medial heel skive foot orthosis (*right*). In the shoe with only the insole under the foot (*left*), the medially deviated STJ axis will cause increased STJ pronation moment since the shoe reaction force is more centrally located at the plantar heel. However, when the varus heel cup of a medial heel skive foot orthosis is added to the shoe (*right*), the resultant medial shift in orthosis reaction force will cause a decrease in STJ pronation moment and an increase in STJ supination moment. Therefore, foot orthoses with varus heel cup modifications, such as the medial heel skive, are more effective at treating symptoms caused by excessive foot pronation due to their ability to shift reaction forces more medially on the plantar foot and, thereby, greatly increase the STJ supination moment acting on the foot

Following up on the ideas embodied within the Tissue Stress Model, Fuller described, in 1996, how computerized gait evaluation and modeling techniques could be effectively used to guide foot orthosis treatment by aiding in the prediction of abnormal stresses within the foot and lower extremity [110]. Three years later, Fuller described how the location of the CoP on the plantar foot relative to the spatial location of the STJ axis may help direct orthosis therapy for foot pathologies resulting from abnormal STJ moments [111]. In later published works, Fuller and Kirby further explored the idea of reducing pathological tissue stress with orthoses and how this could be integrated with the SALRE Theory of Foot Function and an analysis of midtarsal joint kinetics (Fig. 2.5) to guide the clinician toward a better understanding of foot orthosis function and toward more effective foot orthosis treatments for their patients with mechanically based foot and lower extremity injuries [5, 112, 113]. Recent articles on the shift of foot orthosis treatment paradigms away from the Root model of STJ neutral and toward the Tissue Stress Model of treatment have focused on many of the shortcomings of the Root Subtalar Joint Neutral Model that not only lacks research validation but also uses the unsupported concept that “foot deformities” cause “compensations” or abnormal gait patterns during weight-bearing activities [114, 115].

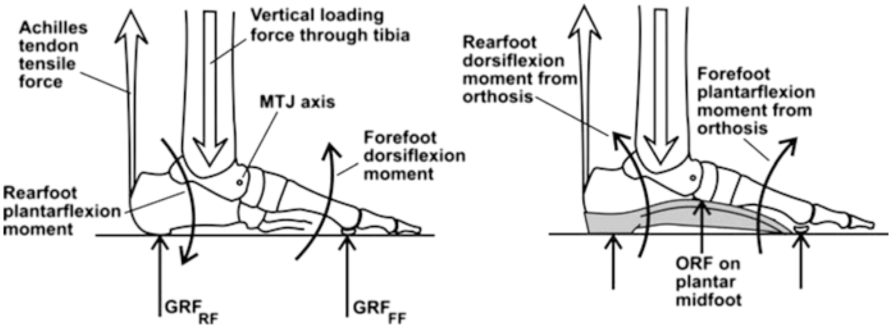

Fig. 2.5 During standing without a foot orthosis (*left*), ground reaction force acting plantar to the rearfoot (GRF_{RF}), Achilles tendon tensile force acting on the posterior rearfoot and vertical loading force from the tibia acting onto the superior talus work together to mechanically cause a rearfoot plantarflexion moment which tends to cause the rearfoot to plantarflex at the ankle. In addition, ground reaction force acting plantar to the forefoot (GRF_{FF}) causes a forefoot dorsiflexion moment which tends to cause the forefoot to dorsiflex at the midtarsal joint (MTJ). Both the resultant rearfoot plantarflexion moment and forefoot dorsiflexion moment tend to cause the longitudinal arch of the foot to flatten. However, when a custom foot orthosis is constructed for the foot that applies a significant orthosis reaction force (ORF) to the plantar aspect of the longitudinal arch (*right*), the resultant increase in ORF at the plantar midfoot combined with the resultant decrease in GRF_{RF} and GRF_{FF} will cause an increase in rearfoot dorsiflexion moment and an increase in forefoot plantarflexion moment. By this mechanical method, foot orthoses help resist longitudinal arch flattening to produce one of the strongest biomechanical and therapeutic effects of orthoses on the foot and lower extremity

In 2001, another new theory of foot orthosis function, the "Preferred Movement Pathway Model," was proposed by Nigg and coworkers that was claimed to be a "new paradigm for movement control." Basing their new theory on previous scientific research, Nigg and coworkers proposed that foot orthoses do not function by realigning the skeleton but rather function by producing a change in the "muscle tuning" of the lower extremity via their alteration of the input signals into the plantar foot during athletic activities. It was suggested that if the preferred movement path is counteracted by the orthosis/shoe combination, then muscle activity would be increased, but conversely, if the preferred movement path is allowed by the orthosis/shoe combination, then lower extremity muscle activity would be reduced [116–118]. Even though the theory of Nigg et al. has received considerable attention within the international biomechanics community, their theory, and all the other abovementioned theories, will require much further research to either support or reject their validity. These and other theories of foot function have been described in much greater detail in the excellent review articles by Payne [119] and Lee [15].

Research on Biomechanical Effects of Foot Orthoses

As mentioned earlier, over the last few decades, there has been a surge in the quality and number of foot orthosis biomechanics research studies on both athletes and nonathletes. Much of the improvement in the quality of research studies on foot orthoses are likely due to many new technological advances that are now available within the modern biomechanics laboratory. These facilities are able to perform advanced biomechanical analyses in a relatively short period of time on subjects using accelerometers, force plates, pressure mats, pressure insoles, strain gauges, and computerized three-dimensional motion analysis. In addition, advanced computer modeling techniques, such as inverse dynamics analysis and finite element analysis, have allowed researchers to better understand the kinetics of gait and investigate the changes in internal loading forces that occur in feet with different orthosis designs. All of these technological advances have allowed researchers to provide very meaningful insights into how foot orthoses biomechanically produce their significant positive therapeutic effects in the treatment of foot and lower extremity injuries [28].

Since early research on the effects of foot orthoses on running biomechanics showed that there was little to no change in the kinematics of gait function with foot orthoses, many doubted whether foot orthoses had any significant biomechanical effect on the foot and lower extremity of the individual [120–123]. However, as the sophistication of biomechanics research has progressed over the past few decades, important new research has now shed more light as to how foot orthoses may change the mechanical function of the foot and lower extremities and help heal injuries in athletes and nonathletes [124–128]. With this newer, more sophisticated research, the multiple alterations that occur in the internal forces and internal moments (i.e., kinetics) of the lower extremities with foot orthoses can now be determined which has produced exciting new research evidence regarding how foot orthoses may produce their biomechanical effects.

Foot Orthoses Alter Foot and Lower Extremity Kinematics and Kinetics

Foot orthoses have been conclusively shown to alter the motion patterns (i.e., kinematics) of the foot and lower extremities in numerous scientific research studies. Research has now shown a decrease in maximum rearfoot eversion angle [120, 121, 128–134], a decrease in maximum rearfoot eversion velocity [121, 128, 133–135], a decrease in maximum ankle dorsiflexion angle [128], a decrease in maximum internal tibial rotation [127, 129, 136, 137], and a decrease in knee adduction [127, 129, 137].

Foot orthoses have also been shown to conclusively alter the internal forces and internal moments (i.e., kinetics) acting on and within the segments of the foot and lower extremity during running. Recent research has shown a decrease in maximum internal ankle inversion moment [126–128, 135] (Fig. 2.6), changes in maximum knee external rotation moment [126], and changes in knee abduction moment [127] during running with foot orthoses. In addition, a decrease in impact peak and maximum vertical loading rate was seen in runners treated with foot orthoses [126].

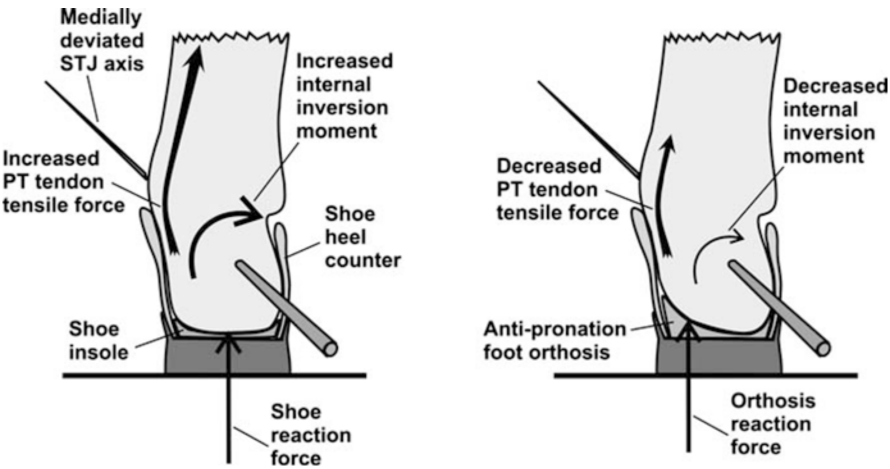

Fig. 2.6 Research has shown that foot orthoses change the kinetics of gait by altering the internal forces acting on the segments of the foot and lower extremity. In the model illustrated above of the posterior aspect of a right foot with a medially deviated STJ axis, when the posterior tibial muscle contracts with increased force to cause increased tensile force on its tendon, an increased internal inversion moment will be measured (*left*). However, when an anti-pronation custom foot orthosis is designed for the foot to shift the orthosis reaction force more medial on the plantar heel and longitudinal arch, the resultant increase in external STJ supination moment from the orthosis (see Fig. 2.4) will cause a decrease in posterior tibial muscle contractile force and a decrease in tendon tensile force which will also result in a decrease in measured internal inversion moment (*right*). It is by this proposed mechanism that foot orthoses may relieve symptoms and heal injuries in the athlete and nonathlete but, in doing so, may also cause little change in measured foot and lower extremity gait kinematics

In addition to the more prevalent research on the biomechanical effects of foot orthoses during running, studies have also shown that foot orthoses significantly affect the biomechanics of walking. Decreased rearfoot pronation and decreased rearfoot pronation velocity with varus-wedged orthoses and increased rearfoot pronation with valgus-wedged were demonstrated in subjects that walked on both varus-wedged and valgus-wedged foot orthoses [133, 134]. In addition, patients with RA that wore foot orthoses for 12 months showed significant reductions in rearfoot eversion and internal tibial rotation [138]. These studies conclusively demonstrate that foot orthoses are able to alter both the motion patterns and internal forces and moments acting within the foot and lower extremity during both running and walking activities. The more recent research on the kinetics and kinematics of foot orthosis function also support the theories mentioned earlier that proposed that foot orthoses work largely by altering the internal forces within the foot and lower extremity by changing the moments acting across the joints of the human locomotor apparatus [5, 25, 93, 99, 106–108, 111–113].

Foot Orthoses Alter Contractile Activity of Lower Extremity Muscles

Research has also shown that foot orthoses significantly affect the contractile activity of the lower extremity muscles during running and other activities. Foot orthoses were found to alter the EMG activity of the biceps femoris and anterior tibial muscles during running [139] and to significantly change the EMG activity of the anterior tibial muscle during walking [140]. Research has shown that changes in foot orthosis design may cause significant changes in EMG activity in many of the muscles of the lower extremity during running [141]. A correlation between perceived foot comfort with different types of foot orthoses and the EMG activity of the lower extremity muscles has also been demonstrated [142]. In addition, in a study of 12 adults with an everted rearfoot posture, foot orthoses were found to significantly decrease the muscular activity of the tibialis anterior, soleus, gastrocnemius, and peroneus longus during walking [143].

Foot Orthoses Improve Postural Stability

As mentioned earlier, there is experimental evidence that foot orthoses can also improve the postural stability of individuals. Postural sway was reduced when subjects wearing foot orthoses were subjected to inversion/eversion and medial/lateral platform movements which indicated that undesirable motion at the foot and ankle may have been restricted and/or the ability of joint mechanoreceptors to detect motion perturbations may have been enhanced by orthoses [85]. Subjects balancing on one foot were likewise shown to have significant decreases in frontal plane CoP length and velocity with medially posted orthoses which possibly indicated foot orthoses enhanced their postural control abilities [86]. In another study involving subjects with excessively pronated feet, foot orthoses produced reductions in medial-lateral sway during bipedal standing indicating improved balance [87].

Foot Orthoses Reduce Plantar Forces and Pressures

Again, as noted earlier, research on the ability of foot orthoses to reduce the forces and pressures on injured or painful areas of the plantar foot provides yet another therapeutic mechanical action of foot orthoses (Fig. 2.7). In a prospective study of 151 subjects with cavus foot deformity, those subjects wearing custom foot orthoses after 3 months showed significant decreases in foot pain, increases in quality of life, and showed three times the forefoot plantar pressure reduction when compared to sham insoles [58]. In 42 subjects with metatarsalgia, foot orthoses were found to not only decrease the metatarsal head pain but also significantly decrease the force impulse and peak pressure at the metatarsal heads [59]. Significant reductions in plantar pressures and loading forces were shown in another study that measured the effects of foot orthoses on both normal and RA subjects [62]. In 81 patients with Type II diabetes, maximum peak plantar pressures were reduced by 30% with foot orthoses [63] and in 34 adolescent Type I diabetic patients both peak pressure and pressure-time integral was reduced while wearing foot orthoses [64]. In a study of eight patients with plantar neuropathic ulcerations that had become healed with custom foot orthoses, it was found that their custom foot orthoses significantly

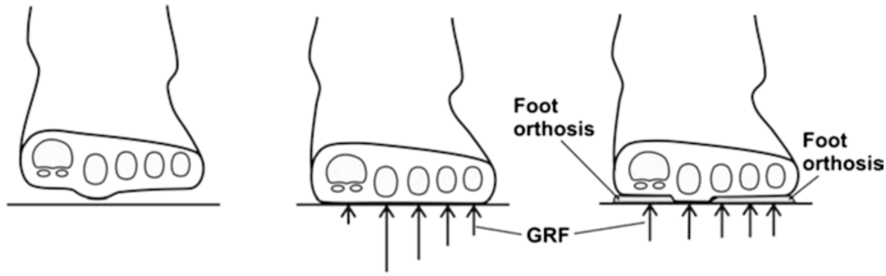

Fig. 2.7 Research has shown that foot orthoses may be designed to reduce the plantar pressures and forces acting on the foot. In the model above, a frontal plane cross section of the metatarsal heads in a foot with a plantarflexed second metatarsal is illustrated. When the forefoot is close to contacting with the ground, but still is non-weight-bearing, the plantarflexion deformity of the second metatarsal is obvious (*left*). However, once the forefoot becomes weight-bearing, the increase in ground reaction force (GRF) that occurs at each of the metatarsal heads will be particularly increased at the second metatarsal head (*middle*) which may cause injuries to the osseous and/or soft tissue structures of the second metatarsal or second metatarsophalangeal joint. To treat the increased compression forces and stresses at the second metatarsal head, a foot orthosis may be designed to increase the GRF plantar to the first, third, fourth, and fifth metatarsal heads and decrease the GRF plantar to the second metatarsal head (*right*). This redistribution of GRF on the plantar foot, away from high pressure areas toward lower pressure areas, is the most likely mechanism behind the ability of foot orthoses to reduce pathologic pressures away from specific areas of the plantar foot

reduced peak vertical pressure, reduced the pressure/time integral, and increased the total contact surface area versus the no-insole condition [61]. In another study using computer-simulated three-dimensional finite element analysis of a foot exposed to different orthosis constructions, orthosis shape was found to be more important in reducing peak plantar pressures than was orthosis stiffness [144].

Conclusion

Foot orthoses have been used for at least 235 years by clinicians as a means to reduce pain, improve gait mechanics, and heal injury to the foot and lower extremity. There is considerable research evidence that supports the therapeutic efficacy and significant mechanical effects of foot orthoses on standing, walking, and running activities. Theoretical explanations as to how foot orthoses actually produce their therapeutic and mechanical effects have been previously proposed and are being continually refined as exciting new research evidence is brought to light and discussed in academic forums. There is great promise for increased understanding and further development of foot orthoses as a valuable therapeutic tool in the treatment of mechanically based musculoskeletal injuries for the athletic and nonathletic population of today and for future generations.

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Athletic Foot Types and Deformities

3

Tim Dutra and Mark Razzante

The feet of athletes of all ages can be categorized as belonging to one of three specific types: rectus, planus, or cavus. Some athletes who are affected with congenital deformities and who suffer from chronic pain, discomfort, or reoccurring injuries can be treated. Examples of treatable deformities are discussed in this chapter. A basic knowledge of these foot types is necessary for athletes, certified athletic trainers, and sports medicine professionals. With this knowledge, sensible and informed decisions can be made in selecting appropriate footwear and orthoses in their sport. This chapter briefly discusses foot motion and mechanics and reviews common sports injuries relating to the deformities of the foot that can predispose athletes to these conditions.

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Normal Foot Motion and Biomechanics During Gait

A brief review of the gait cycle is necessary to understand the pathomechanics of the common athletic injuries we discuss in this chapter [1–5]. The next chapter reviews clinical methods available to perform gait analysis. The gait cycle consists of four key phases: heel strike, midstance, toe-off, and swing phase.

At heel strike, the heel contacts the ground in a slightly supinated position on the lateral aspect of the heel and pronates (more flexible) until the foot contacts the ground. The heel transitions from a supinated position to a more neutral position, and the pronation of the foot allows for adaptation to the ground as the lower leg rotates internally. During midstance, foot pronation decreases as the foot prepares for toe-off. During the toe-off stage, the foot supinates (more rigid) and the heel rises during propulsion. Lastly, the foot goes through the fourth stage, the swing phase as the foot is preparing for heel strike of the opposite foot. Running includes a double float phase in which neither foot is in contact with the surface.

Foot Types

Rectus foot type is a foot with normal foot structure with an average arch and an average calcaneal inclination angle. Injuries to athletes with this foot type typically do not involve instability or abnormal motion available at the joints. Clinically, pes planus and pes cavus foot types are treated most often.

Pes planus is a flat foot (Fig. 3.1), with a moderate or more loss of the longitudinal arch of the foot. Pes planus can be classified clinically into rigid or flexible. Characteristics of a pronated foot include uneven weight distribution, increased flexibility, increased calcaneal eversion, and associated pathologies. Pathologies include hallux valgus, hammertoes, neuromas, medial knee pain, and hip/lower back problems. There are congenital causes and functional causes. Congenital causes include equines, ligamentous laxity, ankle valgus, and peroneal spastic flatfoot. Functional causes include compensated forefoot varus, transverse plane compensation, and leg length difference.

Fig. 3.1 Lateral radiograph displaying pediatric pes planus

In rigid pes planus, the range of motion is decreased at the tarsal and subtalar joints. The arch does not rise with toe rising. Possible causes include a tarsal coalition and peroneal spasticity. Flexible pes planus is physiologic or pathologic, depending on ligamentous laxity, motor weakness in the foot muscles, or bone abnormalities. These can be categorized further into three types.

Functional fiat foot (calcaneovalgus) is the most common type of flat foot with athletes. It is physiologic with a decreased longitudinal arch associated with heel eversion (calcaneovalgus). It is usually not painful or cause of disability in the athlete. Treatment usually consists of adequate heel counter support and orthotic therapy.

Hypermobile flat foot is associated with ligamentous laxity with tight heel chords. Possible causes include tarsal coalition, vertical talus, or accessory navicular. Treatment focuses on stretching exercises for the Achilles tendon and orthotic therapy.

Pes planus with posterior tibial tendon dysfunction evolves through a series of three stages, so it is imperative to recognize and treat this type early and aggressive. In stage 1, the posterior tibial tendon is normal length with the tendon showing degenerative changes. Typically there is mild-to-moderate pain along the posterior tibial tendon. Classically, the pain is localized a few centimeters distal to the tip of the medial malleolus, coursing along to the plantar attachment to the navicular bone. A single heel rise may reveal mild-to-moderate weakness of the tendon. Treatment is conservative with modifying the activity and using orthotic therapy. In stage 2, the posterior tibial tendon elongates, with the rearfoot becoming more mobile. Pain can be along the length of the tendon. The forefoot becomes abducted on the rearfoot, so if viewed from behind "too many toes" are observed. A single heel raise can show significant weakness. Treatment usually requires surgical consideration following an MRI evaluation. In stage 3, there is posterior tibial tendon rupture. The rearfoot becomes rigid and a fixed rigid flatfoot develops. This deformity is a dramatic presentation. A surgical arthrodesis can be required due to the severe pain with this progression.

Pes cavus is a high-arched foot with an elevation of the longitudinal arch, which is present with and without weight bearing. The toes can be contracted in the more severe cases. Characteristics include decreased pronation, rigid foot, weight unevenly distributed, and a tendency for later ankle instability leading to frequent inversion ankle sprains. There is limited range of motion and poor shock absorption. In the athlete, the cavus foot is usually a static idiopathic presentation. Neuromuscular causes are progressive in nature. Pes cavus can be congenital or functional in nature. Congenital causes include plantar flexed first ray, peroneal spasm/weakness, and metatarsus adductus. Functional causes include leg length difference, uncompensated rearfoot varus, partially compensated rearfoot varus, or compensated rigid forefoot valgus. Treatment consists of shoes with cushioning, orthotics for support, and stretching exercises of the plantar fascia and Achilles tendon.

Functional Foot Disorders

Functional foot disorders can be in the frontal, sagittal, or transverse planes. The frontal plane involves the varus or valgus of the rearfoot or forefoot. These can be uncompensated, partially compensated, or compensated. The sagittal plane involves equinus, and the transverse plane involves femoral or tibial torsion.

Examples of Foot Deformities in Athletes

- Rearfoot varus: a frontal plane deformity where the calcaneus is inverted when the foot is maintained in a subtalar joint neutral position.
- Rearfoot valgus: a frontal plane deformity where the calcaneus is everted when the foot is maintained in a subtalar joint neutral position.
- Metatarsus adductus: a transverse plane deformity where the forefoot is adducted when compared to the position of the rearfoot. This is also called a c-shaped foot.
- Plantarflexed first ray: a sagittal plane deformity where the first metatarsal is plantarflexed in comparison to the other metatarsals when the foot is in its neutral position.
- Ankle equinus: a sagittal plane deformity where there is less than 10° of available dorsiflexion at the ankle joint when the subtalar joint is in its neutral position and the midtarsal joint is fully locked.
- Forefoot valgus: a frontal plane deformity where the forefoot is everted in reference to the rearfoot when the foot is maintained in a subtalar joint neutral position.
- Forefoot varus: a frontal plane deformity where the forefoot is inverted in reference to the rearfoot when the foot is maintained in a subtalar neutral position.

Lower Extremity Pathology

The most commonly reported athletic foot and ankle pathologies are Achilles tendinopathy, plantar fasciitis, and stress fractures [6]. Most common lower extremity pathologies are a result of abnormal foot function. This section reviews which foot types are responsible for causing these pathologic conditions. Evidence-based orthotic treatment recommendations for many of the following conditions are included in Chap. 11.

Calcaneal Apophysitis

Calcaneal apophysitis is a painful condition that affects the growth plate of the calcaneus in young athletes in the 8–15 year age group. Pain is experienced with running and jumping activities in a variety of sports such as basketball, baseball, and

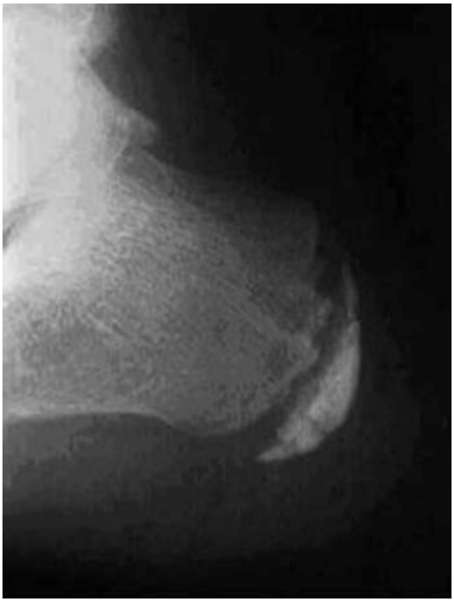

Fig. 3.2 Lateral X-ray view of young athlete with calcaneal apophysitis

soccer. Pain can be reproduced with the squeeze test, applying medial and lateral calcaneal compression to the heel. This condition is related to tight posterior muscle group and plantar fascia. Foot types which can be associated with this condition include forefoot varus (compensated or partially compensated), forefoot supinatus, flexible forefoot valgus, or a compensated equinus or transverse plane deformity. With regard to athletic shoes, a negative heel and poor heel counter can contribute to the problem, as well as poor cushioning of the shoe (Fig. 3.2).

Kohler's Disease

Kohler's disease is osteochondritis affecting the navicular bone in young children ages 3–9 years old. Symptoms affect the dorsal medial aspect of the navicular area, often causing an antalgic gait with increased lateral column weight bearing to decrease pain.

Freiberg's Disease

Freiberg's disease is osteochondrosis of the lesser metatarsal heads. There is a loss of blood supply to the metatarsal heads, generally affecting the second metatarsal head. Most commonly it occurs in the 13–15 age group. Pain and swelling are localized and motion is guarded.

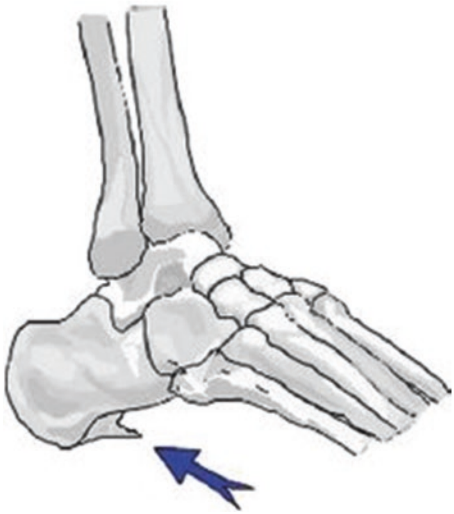

Fig. 3.3 Plantar calcaneal heel spur at origin of plantar fascia

Plantar Fascia Pathology

Often referred to a heel spur syndrome, plantar fasciitis, or plantar fasciosis, this pathology is a common condition with pain at the medial plantar aspect of the calcaneus with pain classically in the morning or following periods of rest. Histologic examination of this process has confirmed a pathology of degeneration rather than inflammation and supports the term fasciosis [7]. Pain can be present during activity. This pain may be associated with inflammation at the origin of the plantar fascia on the calcaneus or as a periosteal reaction to heel spur formation. Both pes cavus and pes planus can lead to this condition. With pes planus the plantar fascia is chronically stretched during foot flattening with excessive calcaneal eversion. Conversely, with a high arch the plantar fascia that is taut and contracted can also lead to this condition. Most causes of heel spur syndrome are mechanical. X-rays can demonstrate the progression of minimal periosteal involvement which can eventually lead to plantar spur formation (Fig. 3.3).

Sesamoiditis

Sesamoiditis causes pain and inflammation plantar to the first metatarsal head from excessive pressure to the area during activity. Pain symptoms are present with joint motion and with muscle testing. Predisposing conditions include plantarflexed first metatarsal, enlarged sesamoids, trauma to the area, and inadequate shoes. X-ray evaluation can be difficult due to bipartite sesamoids. A bone scan may be necessary in some cases. Orthoses can help this condition by controlling pronation and accommodating the sesamoid area with forefoot extensions such as a reverse Morton's extension which supports metatarsals 2–5 and effectively off loads the area (Fig. 3.4).

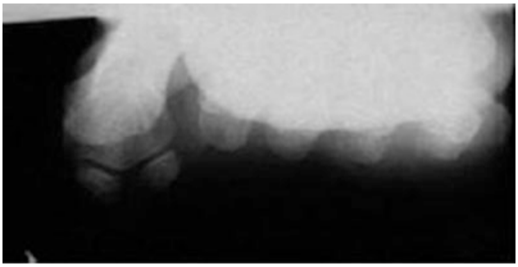

Fig. 3.4 Plantar axial view of the sesamoids demonstrates abnormal tibial sesamoid with fracture. It is important to differentiate between bipartite and fracture of the sesamoid. Sometimes a bone scan is needed to confirm diagnosis

Fig. 3.5 Stress fracture of the shaft of the third metatarsal

Stress Fracture

Stress fracture is usually caused from repetitive trauma to the area. Faulty foot mechanics can cause and aggravate this painful condition. Pain is usually local with mild edema and erythema and made worse with activity. Commonly the neck or shaft of a lesser metatarsal or a sesamoid is involved. Calcaneal stress fractures may also occur after a rapid increase in activity. Orthoses can be very helpful in controlling the faulty foot mechanics. Adequate shock absorption is needed with shoe gear and orthotics (Fig. 3.5).

Fig. 3.6 Radiograph displaying avulsion fracture of fifth metatarsal base

Fifth Metatarsal Fractures

Along with the aforementioned metatarsal stress fractures, the fifth metatarsal is a commonly fractured metatarsal due to its location. This metatarsal bears much of the weight as it is the outermost metatarsal of the lateral column. In cavus feet, there is increased pressure placed along the lateral column and fifth metatarsal and fractures just distal to the base, or Jones fractures occur. Excessive pull from the peroneus brevis or lateral plantar fascia band during an inversion injury may result in an avulsion fracture off the fifth metatarsal base (Fig 3.6).

Lisfranc Fracture/Dislocations

The Lisfranc ligament connects the base of the second metatarsal to the medial cuneiform and holds the midfoot in alignment across the transverse arch. Injuries to this ligament and surrounding metatarsals may occur when an athlete has a forced dorsiflexion of the midfoot on the rearfoot or experiences a forceful twist to the midfoot. A dislocation occurs when the Lisfranc ligament is ruptured and there is a splaying of the first and second rays with possible partial or complete lateral deviation medially or laterally or the entire forefoot shifts medial or lateral due to the Lisfranc complex disruption. Often times these soft tissue ruptures are joined with fractures of one or a combination of the metatarsal bases, cuneiforms, and cuboid (Fig. 3.7).

Ankle Sprains

Ankle sprains, especially inversion type, are very common in athletics. The injury involves the ligamentous structures of the ankle, most commonly the lateral collateral ligaments due to inversion stress to the ankle in an unstable position. Frequent ankle sprains or lateral ankle instability can be associated with ligamentous laxity

Fig. 3.7 Radiograph displaying Lisfranc fracture/dislocation

Fig. 3.8 Clinical presentation of acute inversion ankle sprain with erythema and edema of the lateral aspect of the ankle

or supinated foot types primarily with the heel inverted, especially with a forefoot valgus deformity or a rearfoot varus (uncompensated or partially compensated) deformity. High ankle sprains involve an injury to the syndesmosis between the tibia and fibula. These injuries are usually more painful and symptomatic above the ankle joint, and pain can be elicited with external rotation of the foot on the leg. Orthoses addressing the lateral column instability can help with a forefoot posting. Mid-to-high top athletic shoes can provide additional ankle support for the athlete during activity (Fig. 3.8).

Patellofemoral Dysfunction

With patellofemoral dysfunction patients have chronic symptoms of pain around the patella with activity. Contributing factors include weak vastus medialis, anatomical variation of the patella and knee joint, and abnormal pronation which increases transverse plane torsion at the knee joint. This condition can be controlled with functional orthotics by reducing subtalar joint pronation and internal rotation of the tibia, allowing the patella to track primarily in the sagittal plane.

Medial Tibial Stress Syndrome

More commonly known as "shin splints," medial tibial stress syndrome occurs as an overuse injury with repeated stress on the muscles attached to the tibia as well as the tibia itself. It may involve periosteal reaction or small microtears in the involved muscles. Repeated torque on the tibia may produce stress reaction of the tibia.

Interdigital Neuroma

Interdigital neuroma presents with pain located in the interspace, most commonly the third interspace. This pain typically radiates to the adjacent digits. The symptoms increase with activity. Neuromas are aggravated by tight shoes and associated with abnormal subtalar and midtarsal joint pronation which causes an increase in the transverse plane motion at the metatarsals. Orthoses attempt to control the excessive transverse plane motion of the forefoot during midstance and propulsion during gait, specifically between the medial and lateral columns. The medial column is made up of the first three metatarsals articulating with the cuneiforms. The lateral column is made up of the fourth and fifth metatarsals articulating with the cuboid. A metatarsal raise or "met cookie" is helpful in relieving the pain, as well as switching to a wider shoe.

Achilles Tendonopathy

The most common area of involvement of the Achilles tendon is the areas proximal to the insertion of the calcaneus. There can be an inflammation of the peritendon or a degeneration of the tendon itself. It may be caused by tightness of the Achilles tendon or strenuous activity. A pronated foot type can cause increased frontal plane torqueing of the tendon, much like wringing a wash rag. Posterior heel pain can occur from Achilles insertional tendonitis, where the enthesis becomes painful often seen with an upward growing bone spur. The Achilles pad or collar in the heel of the shoe must not irritate the tendon (Fig. 3.9).

Fig. 3.9 Achilles tendonitis of the *left foot* with severe inflammation as compared with the *right foot*

Posterior Tibial Tendonitis

Posterior tibial tendonitis presents with pain behind the medial malleolus or at the insertion of the tendon into the navicular bone. It is usually seen with a pronated foot type that pulls the tendon at the insertion at the navicular bone. Commonly it is associated with an accessory navicular tuberosity (os tibiale externum). A spontaneous rupture or chronic dysfunction can lead to a markedly pronated foot ("too many toes" sign). Orthoses are often necessary to treat this condition and control the pronatory forces.

Hallux Abducto Valgus

Hallux abducto valgus involves a prominence of the medial or dorsomedial aspect of the first metatarsal head (Fig. 3.10). There is an associated increased adduction of the first metatarsal. Commonly there is hypermobility of the first ray with a forefoot adductus type of the foot. There are four basic stages of hallux abducto valgus deformity. In stage 1, there is lateral displacement of the proximal phalanx relative to the first metatarsal head. In stage 2, there is hallux abductus with the hallux abducted against the second toe. In stage 3, there is a development of metatarsus primus adductus leading to an increased angle between the first and second metatarsals. Stage 4 is the end stage with a dislocation of the first metatarsal phalangeal joint with loss of joint congruity. Orthoses are most useful in the treatment of the earlier stages because they can control the abnormal intrinsic and extrinsic muscle function.

Fig. 3.10 Radiograph displaying hallux abducto valgus

Hallux Limitus/Rigidus

Often referred to as a "dorsal bunion," the continuum of hallux limitus is the decreased range of motion at the first metatarsophalangeal joint which eventually progresses to minimal or no range of motion and referred to as hallux rigidus (Fig. 3.11). The effect this has on athletes is the lack of ability to dorsiflex the first metatarsophalangeal joint which can limit crouching or cause them to abduct their foot in propulsion. As this progresses, often times a dorsal exostosis forms on the metatarsal head, which can become irritated by the overlying shoe gear.

Turf Toe and Soccer Toe

These terms describe sprains of the first metatarsophalangeal joint with possible ligamentous or capsule tears. Turf toe is a hyperextension injury occurring when the athlete's toes are dorsiflexed and anchored into the ground with excess force driven from the rearfoot into the ground, often times from another athlete falling on the foot and jamming it into the ground. This can also occur from a traumatic or repeated kicking of a ball or other object.

Fig. 3.11 Radiograph displaying hallux limitus

Hammer Toe Deformity

Hammer toe deformity involves a contraction of a digit sometimes with varus rotation of the toe. Possible causes can be abnormal pronation of the subtalar joint, plantarflexion of the metatarsal, reduced lumbrical muscle function, a forefoot valgus, extensor tendon substitution, or hallux abducto valgus deformity. Variations include claw toes and mallet toes.

Tailor's Bunion

Tailor's bunion is a deformity involving a painful enlargement or prominence of the fifth metatarsal head. Causes include increased subtalar joint pronation, dorsiflexion or plantarflexion of the fifth ray, or an uncompensated varus deformity. The fifth ray becomes subluxed. Abnormal pronation alone does not cause this deformity. Painful fifth metatarsal heads can originate from an enlarged metatarsal head, deviation of the metatarsal bending outward, or splaying of the fifth metatarsal from the fourth. Often orthoses will not help this condition if abnormal pronation is not causing this deformity in the athlete.

Toe Nails

Painful toe nails can result from shoe gear too small, constantly causing trauma to the longer toes. This is often seen with the hallux or second toe experiencing repeated trauma at the end of a tight shoe. The repetitive trauma can result in a subungual hematoma, or blood pooling between the nail bed and plate. Ingrown toe nails may be seen from an irritated, incurvated nail with trauma, tight shoe, or incorrect nail trimming. The medial border of the hallux nail is commonly irritated from narrow toe boxes and can become infected if not properly trimmed and cared for.

Blisters

Friction and moisture lead to the production of blisters on the foot and ankle. Usually they occur over bony prominences in areas of increased pressure either from the shoe or from increased repetitive ground reactive forces. Modification of socks and shoe gear can reduce the prevalence of blister formation.

Treatment

Treatment considerations for athletes with these common conditions involve proper athletic shoes for their sport and often functional orthoses as well. Prior to orthotic treatment, taping and padding will give a good prognosis of biomechanical control for the athlete. Remember, the orthosis is only as good as the athletic shoe that you put it in. Athletic shoes and orthoses need to be continually monitored for wear and support of the athlete. Depending on the sport, size of the athlete, and the intensity of the sport, the athletic shoe may need to be replaced several times during a season. Shoes that the athlete trains in must also allow for proper support and control for the athlete. Deformities such as hallux abducto valgus, hammer toes, and tailor's bunions must be specially addressed in fitting the athlete for shoe comfort and design. The orthosis must fit well in the shoe and sit properly in the foot bed. Some sports require a low-profile type of orthotic device, as well as less bulky forefoot extensions or cushioning. Often times a rearfoot post will not be fit in the shoe and thus the unposted orthosis will fit in the shoe better. Ultrathin flexible graphite or cobra style orthotics provide a low-profile device that works well in athletic footwear.

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Clinical Use of Gait Analysis for the Athlete

4

Michael Chin

Observational Gait Analysis

Observational Gait Analysis (OGA) has been utilized by clinicians for more than a century and still used in practice today. OGA is an inexpensive method for obtaining a visual assessment of the human gait, but has limitations [20, 21]. The primary criticism of OGA is the limited reproducibility and usefulness of the data and/or subjective observations. Researchers and clinicians began to work on to standardize OGA by creating the Physician Rating Scale (PRS) [1]. The researchers would evaluate six variables on a 2–4 point scale. An example of one of the variables is the knee position at mid-stance. This variable shows a good to excellent reliability, yet only has a moderate level of accuracy.

Research suggests that the more variables observed, the less accurate are the observations; thus future research will hopefully yield more repeatability and add reliability [2]. The formal methods of OGA are The Rivermead Visual Gait Assessment or the Observational Gait Scale. They both improve the reliability, but not so for the accuracy [3–5].

So, one would think, to observe abnormal gait, it would be essential to understand the normal human gait. Though, in the last 30 years, there is no universally accepted model of the normal human gait [6]. Two of the reasons for inconsistencies are the lack of raters lacking knowledge of the normative values of the variables being tested and the compensation values of an abnormal gait study [2, 7]. Theories behind gait evaluation and biomechanics vary for each discipline. Disciplines that utilize gait analysis are podiatrists, physical therapists, orthotists and prosthetists, exercise physiologists, and neuroscientists, among others. Even though there may be differing theories on human movement, we, as practitioners, should take the time to understand each other's perspectives to build a common practice [4].

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Humans move in the manner that is most metabolically efficient and causes the least amount of discomfort. This is illustrated by world-renowned biomechanist Dr. Benno Nigg's suggestion that a running shoe should be chosen based on comfort [8]. Acceleration and deceleration of the body affect the metabolic energy costs with each step, whether running or walking. Energy conservation can be controlled by the vertical and lateral displacement of the human's center of mass (CoM). To find the CoM, the landmarks are just anterior to the second sacral vertebra and midway between the hip joints. It is impossible to ambulate without vertical and lateral translations of CoM [9]. Saunders and colleagues in 1953 used the term "determinants of gait" to describe key gait strategies humans use in order to control the CoM and minimize the metabolic cost of gait. Researchers have added a sixth determinant to Saunder's original five [5, 10, 11]. As researchers fundamentally agree on the various movements, there are researchers questioning their role of energy conservation. With an understanding of these determinants, it is paramount for mastering the fundamentals of gait.

1. *Foot mechanism*: The foot minimizes the vertical displacement of the CoM by elongation of the foot upon heel strike and the lengthening of the foot with plantarflexion at toe-off.
2. *Ankle mechanism*: The heel, again, effectively minimizes the vertical displacement at the ankle as it is positioned posterior to the ankle joint.
3. *Knee flexion in stance phase*: Knee flexion in mid-stance shortens the leg, which minimizes vertical displacement of the CoM. Peak knee flexion is approximately 15° in normal walking [9].
4. *Pelvic obliquity*: The frontal plane movement of the hips reduces the vertical displacement. In an alternating fashion, the pelvis tilts with hip flexion and extension. When the hip is at its high point, the pelvis slopes down with the swing phase leg being lower. This pelvic tilt conserves energy by minimizing vertical displacement of the trunk. The pelvis drops 4–5° during the normal gait cycle [9]. This determinant presupposes that the swing leg can be shortened adequately to clear the ground through knee flexion and ankle dorsiflexion.
5. *Pelvic rotation*: Transverse plane pelvic rotation brings the hip joint forward during flexion and backwards during extension. The hip rises and falls vertically during this movement. This conservation of hip ROM is more efficient than a hip that is fixed in the transverse plane, and results in decreased vertical movement of the hip, further conserving energy and providing a smoother movement pattern [5, 9].
6. *Lateral displacement of body*: Preservation of balance and conservation of energy is achieved by maintaining a narrow base of gait. Energy is conserved by minimizing lateral movement of the CoM. When performing gait analysis, one should maintain a firm understanding of these determinants. Any departure from these parameters should raise questions or concerns from the observer.

Technological Advances in Gait Analysis

In the 1970s, instruments such as pressure mat technology and high-speed video created a new format for obtaining a gait analysis. The continued evolution of software interfacing with force platforms, high-speed video, accelerometers, and more powerful computers allows for a more sophisticated analysis [10, 12]. While video gait analysis has not completely integrated in the clinical model, it has the opportunity in research settings for a better understanding of human movement, and is becoming a more useful clinical modality for sports medicine practitioners.

As stated earlier, OGA is still used today in many of our athlete's assessments, but there is much subjectivity of what the human eye can track and process. The human eye can only process at a rate of 1/12 of a second [13].

Currently, Video Gait Analysis (VGA) systems can capture as fast as 100 frames per second and as slow as 30+ frames per second with high definition 4K resolution. Thus, with the ability to capture an athlete's gait with that frame speed, we can slow down the video or play frame-by-frame to hone in on the details at each anatomic segment.

Historically, running and walking mechanics were recorded using filming techniques in the 1800s [14]. Currently, as technology continues to evolve, there are a number of options for clinicians to implement Two Dimensional Video Gait Analyses (2D VGAs). These include a standard hand-held video camera, smartphone or tablet VGA applications (Hudl® and Dartfish Express®), and computer-based software and camera capture options (Dartfish®). The advantages with these platforms are that the clinicians can provide feedback to the athlete with good clinical data with real-time feedback. As technology continues to evolve, the information provided through clinical gait analysis has become very precise and can offer an array of visual, pressure, motor, and neural-related data. This information used to be limited to expensive university gait laboratories.

When assessing an athlete during rehabilitation from an injury or to proactively prevent injury from occurring, using clinical gait analysis can provide functional and quantitative information to aid in improving clinical outcomes. VGAs in particular can be used to assess for anatomic asymmetries, evaluation of ranges of motion, optimizing comparisons of angles, and assess the athlete under dynamic conditions. A thorough understanding of the normal walking and running gait is very important in achieving the athlete's goals as discussed when using observational techniques [15].

There is a concert of events that happen during the gait cycle that is comprised of the synchrony of the kinetic chain. The foot is the point of contact to the ambulatory surface and provides the feedback and initiation of the kinetic chain. What the foot does at the time of impact include adaptation to terrain, leverage for propulsion, and proprioception for balance and positioning. Shoe wear and orthotics can facilitate proper alignment, but can also create instances of over-correction and under-correction. What we also need to realize is that the proximal structures of the lower extremity, even at the spinal level, can alter the mechanics down the kinetic chain [16]. Three-dimensional kinematic data obtained from pressure analysis through force plate capture, dynamic EMG, and motion analysis can provide the detail of the kinetic chain by joint coupling and specific calculations of loading forces, neuromuscular patterns, and motion about a joint axis [16, 17].

Temporal-spatial parameters such as cadence in steps per minute, angle and base of gait, stride length, arm swing, movement of the trunk, and rise of the body are assessed and measured [4, 5, 9]. The clinician should be aware that the athlete's height, sex, and extrinsic factors such as length of runway, treadmill, or even room size affect temporal gait parameters [7].

A good clinician uses it to confirm what they already suspect and has visual evidence to share with the athlete. VGAs should not replace a thorough and comprehensive history and physical examination. It is an excellent instrument for assessing the response to interventions including, but not limited to:

Symmetry assessment
Footwear suggestions
Custom orthotics/insole use
Gait reeducation
Pre to post surgical outcomes

Prior to performing an athlete's VGA, the clinician should obtain the following:
Past History

Previous injuries
Training routine
Training goals
Running form modifications
Previous treatment including orthotic use, shoe selection
Distance
Running surfaces

Physical exam

The clinician should perform a hands-on clinical examination of the athlete. Be aware of any current injury, as you do not want to perform VGA while athlete is severely injured, as this will skew the information presented.

If the VGA is being utilized for prehabilitation purposes, the clinician will need to know what the athlete's status is prior to examination, what the surgical procedure being performed will be, and the proper time to reassess once the patient is cleared for activities.

Clinical importance of VGA has been more so the ability to evaluate for injury risk factors, identify core imbalances, previous injuries and the levels of compensation due to the prior injury, and body alignment and stability.

There are multiple ways to capture an athlete's gait for analysis. These are the methods that are currently utilized in clinical settings:

2D VGA
Force Plate Recordings
3D Human Motion Analysis
Dynamic Electromyography
Energy Cost Measurements or Energetics

2D Video Gait Analysis

As noted in the previous section, 2D VGA is likely the least expensive option for assessing an athlete's gait in a private practice setting (Fig. 4.1). Systems can record single or multiple cameras with synchronized or non-synchronized views. These perspectives can be compared to accepted joint angulations that have been researched using 2D analysis. When looking at the more elaborate 3D Human Motion Analysis, the sagittal angulations of the hip, knee, and foot can be closely referenced to the 2D imaging [17]. Observing subjects' gait from lateral, anterior, and posterior views to assess sagittal and frontal plane movement normally assesses kinematics. Some labs use ceiling-mounted cameras directly over the subject to capture transverse plane motion. Key kinematic angles and events as described by Kirtley [4] are:

Ankle dorsiflexion at contact
Maximum rearfoot eversion
Knee flexion at contact

Fig. 4.1 2D video gait analysis. Photo courtesy of The Running Institute

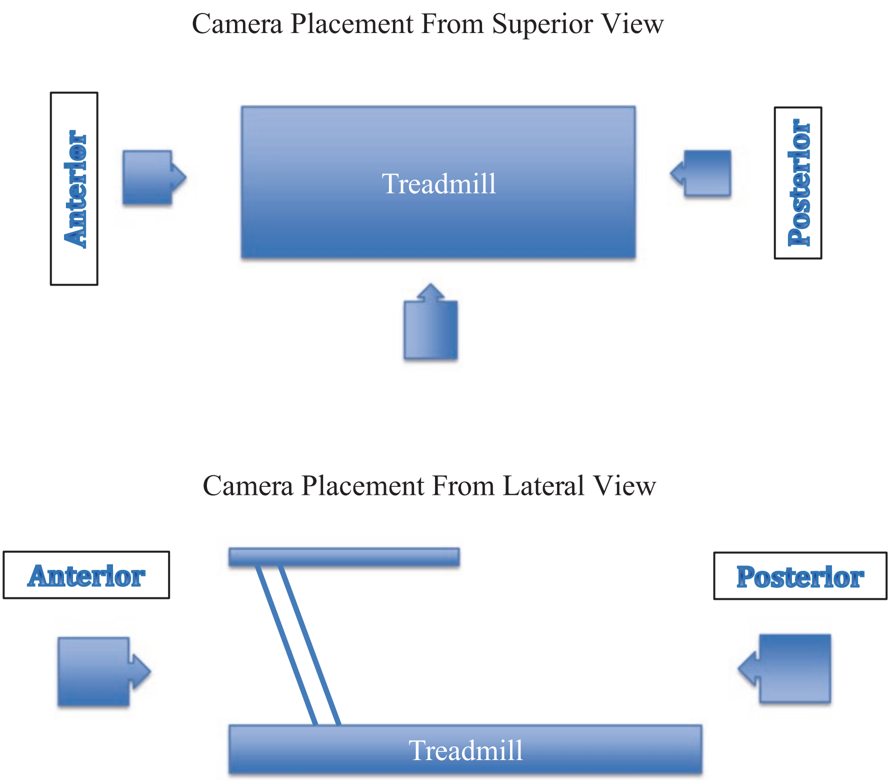

Fig. 4.2 2D VGA office setup schematic. Illustration credit The Running Institute

Knee adduction in late stance
Ankle plantarflexion during push-off
Knee flexion in swing

Since most clinicians are likely to use in-office VGAs to assess their athletes, a suggested guide to obtain an optimal VGA is provided. An example schematic of a 2D VGA setup is noted below (Fig. 4.2).

Important Guidelines for in-office VGA:

1. It is important to provide a proper sized surface to allow the athlete to run without feeling constricted or confined. The treadmill should have a deck surface between 45–60 in. long and 16–20 in. wide. For tall or competitive runners, the length may be more than 60 in. to allow for longer stride length to occur.
2. There should be no visual obstructions to the camera (i.e., side handles, braces, or cords) along with a clean background to avoid image interference.
3. There should be a way to measure a standard distance for analysis. Many systems have a measuring device imbedded in the software to account for this.

4. For optimal VGA capture, to reduce the blurring and elimination of shadows, use LED lighting.
5. When performing VGAs, the camera angle can affect the outcome of the angles being drawn and assessed. The camera should be placed on a stationary location to the treadmill at 90° to the subject being captured.
6. Skin markings should be added prior to the assessment for better bisections to allow for better angular measurements.
7. The athlete should warm-up prior to video capture to find a comfortable pace and speed for the assessment.
8. The runner should find a comfortable and consistent running speed.
9. The clinician should determine whether they would like a full body versus anatomic regional assessment [18].

Excellent examples of lateral, posterior, and anterior camera angles of the lower body are noted (Fig. 4.3a–c). Photo credits Paul Langer.

Peak Pressure Analysis

The pressure analysis is valuable for obtaining the peak pressures throughout the gait cycle. This can help identify areas of abnormality at the different points of pedal contact. From this information, the clinician can develop the correct methods in biomechanical control from the use of orthotics, shoe wear, and muscular reeducation [19].

For the longest time, floor plate mounted 3D force plates were used to determine ground reaction forces and calculation of joint moments via inverse dynamics. The trending focus has been on creating more portable solutions operated via shoe-insoles based on pressure distribution. Instead of in-shoe sensors, the newest way to capture pressure measurements is the use of treadmills with either 3D force plates or pressure plates. There are limitations that are noted with this technology. The findings are that portable solutions cannot measure forces in 3D and certain restrictions in joint force or moment calculations have to be considered (Fig. 4.4).

Human Motion Analysis

VGAs have now evolved to include the use of electromyography and ground reactive forces using force plate technology. Human motion analysis is more comprehensive and is inclusive of:

Human motion analysis can be separated into three major measurement areas:

1. **Kinematic** measures focus on motion and the detection spatial temporal parameters like joint angles or walking speed and are typically operated via multiple video cameras, active or passive marker-based infrared camera systems or goniometer or inertial sensor-based technology.

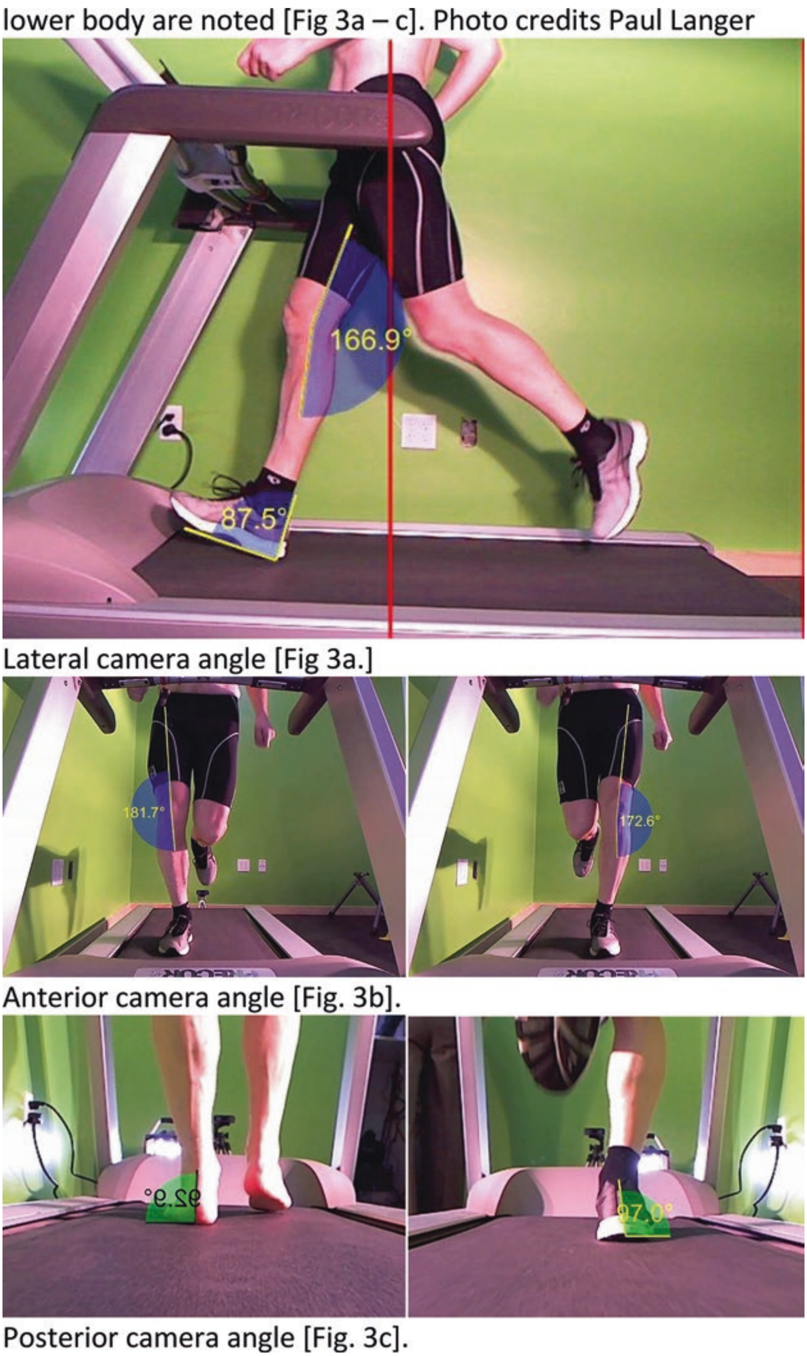

Fig. 4.3 Lateral camera angle (**a**). Anterior camera angle (**b**). Posterior camera angle (**c**)

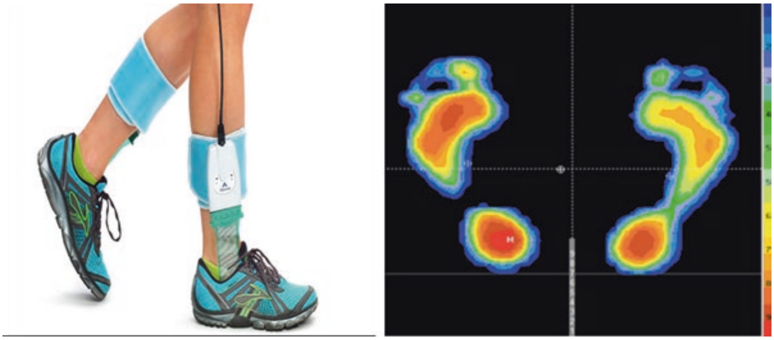

Fig. 4.4 Peak pressure analysis with in-shoe pressure sensors. Photo credits Teksan

Fig. 4.5 Motion analysis using kinematic, electromyography, and kinetic capture

2. **Electromyography** (EMG) detects the electrical muscle innervation in dynamic and postural/static tasks and describes the neuromuscular control behind human motion tasks.
3. **Kinetic** measures forces acting around joints, detects ground reaction force in walking, running, and jumping activities, or quantifies pressure distribution patterns [15].

Typically, all three areas are combined in biomechanical, clinical, or ergonomic motion lab setups. The latest software technology allows one to easily integrate them in any desired configuration, starting from simple 1 to 2 sensor setups up to complex full body analysis covering all major areas of biomechanical measurements (Fig. 4.5). Photo credits Noraxon USA

New Trends in Sensor Technology and Analysis Design

Inertial sensors are becoming smaller and more portable. The setup is much easier for clinicians to apply and to acquire the information. The sensors are wireless and can be done in smaller clinical settings or in the field. The sensors consist of 3D accelerometers, 3D gyrometers, and more. Since the sensors are portable, clinicians can capture real-time data while the athlete is performing their sport of choice. Biofeedback treatment protocols can be applied due to the real-time data feed.

EMG technology is also becoming easier to apply, as they no longer need the bundle of wires connected to the electrode/detection site. The setup time is reduced and the elimination of the wires reduces the restriction of movement during the movement capture.

With technology improving and the ability to capture data becoming easier to perform in the clinical setting, clinicians can obtain valuable information to improve their outcomes when treating their athletes. The terms Video Gait Analysis, Peak Pressure Analysis, or Motion Analysis are becoming commonplace in an athlete's vocabulary and may become the gold standard of care in rehabilitation and preventative measures in the athlete.

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Athletic Shoe Evaluation

5

David Levine

Athletic footwear has been in existence since the 1800s when track competitors used spikes on their leather shoes. The leather fit poorly and the shoes would get stretched out easily making them useless very quickly. Late in the 1800s the Keds Company was born with the innovation of using rubber soles. Emphasis in the early 1900s was on basketball footwear. The main manufacturers in the athletic shoe market at that time were Adis and Rudolph Dassler—ultimately to become Adidas. They were making athletic footwear by hand for basketball and even some tennis players. The market for athletic shoes changed in the early 1970s when Frank Shorter won the Olympic gold medal in the marathon. By then Nike was building a presence based on their innovations in the running shoe market. This happened to coincide with America's running boom. The demand for running shoes took off and so did Nike. As fitness became a major emphasis in this country, other forms of exercise such as aerobics started gaining popularity. Reebok capitalized on this and aimed its marketing and footwear to this niche.

Competition in the athletic shoe market has intensified over the last 30 years. Athletic footwear is no longer just for athletes. Having the right look and the right shoe is very important to the younger age groups. In addition, the shoe companies have attempted to market as many segments of the population as possible in order to sell more sport-specific shoes. With all of this emphasis on the athletic shoe, the question often asked is whether athletic shoes are actually good for your feet. The answer is not a simple yes or no. In order to provide the best answer to that question, an understanding of the shoe itself, its anatomy, and how it functions will lead to answering that question.

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Anatomy of an Athletic Shoe

Review of shoe anatomy, key features, and function will be presented (see Chap. 1 for comparison of historical shoe anatomy designs). All of the parts of a shoe have names, and knowing these names will help to discuss footwear intelligently and consistently. Understanding shoe anatomy and thus shoe function is analogous to learning human anatomy, one needs to understand anatomy before learning physiology.

Last

The last of the shoe ultimately determines how the shoe will fit a particular foot type. Currently, lasts are made of plastic, but in previous times they were made of wood. The last will determine the width toe box, depth of the toe region, toe spring, and heel height. Mass-produced shoes are made from lasts that are typical of common foot structure, whereas custom shoes are made from individual lasts specific for that person and the type of shoe that is desired.

Toe Box

This is the width of the toe region. Some shoes come to a point and some are more squared in their shape. Depending upon the toe shape of the individual will determine what should fit the best. Toe box can also include the depth or height of the toe region. If toes are contracted or overlap each other then as deep a toe box as possible is needed.

Vamp

This is the part of the shoe where the laces are located. Depending upon the angle of the foot in the region of the instep will determine the shape or style vamp that should work the best. For instance if someone has a high instep then increased room is needed in this region.

Balmoral Versus Blucher

Bal is a front-laced shoe in which the quarters meet and the vamp is stitched at the front of the throat. Bal is short for “Balmoral,” the Scottish castle where this style was first introduced. Blucher is a style where the quarters flap opens at the vamp, giving extra room at the throat and instep in fitting. Most athletic shoes are made with a modified bal style.

Outer Sole

This is the bottom of the shoe that interfaces with the ground. There are a variety of different materials that are now utilized for outer soles depending upon the activity for which the shoe is designed. Some are more durable than others. In the early 1970s the waffle sole became very popular when its inventor, Bill Bowerman, was experimenting with soling material and a waffle iron.

Midsole

This is the location found between the outer sole and the upper of the shoe. Development of different density midsole materials has affected the design of many athletic shoes. In addition, athletic shoe manufacturers have experimented in this region of the shoe with ways to try and control the biomechanics of the foot.

Upper

This is the part of the shoe that encloses the foot. The upper is what encloses around the foot, decides the shoe style as well as breathability.

Heel Counter

This is within the upper of the shoe and supports the heel around its medial and lateral sides. Some shoes have a substantial heel counter in order to provide motion control and some leave this out completely. Whether a shoe has a heel counter depends also upon the particular activity for which the shoe was designed.

Function of Athletic Shoes

Initially athletic shoes were made with only function in mind, but that was at a time when there was very little information available concerning the biomechanical aspects of the human foot. Basketball, tennis, and football each had shoes specific for their sport in the early 1900s. In the 1950s that changed when sneakers became a fashionable item for the younger generation. The running boom changed that again as function became important again. As important as function is to athletic shoes, fashion is never far behind though. Selling shoes has always been the priority of the footwear industry. In order to sell shoes, appealing design is necessary. Often the fashion characteristics of a shoe outweigh the function in the mind of consumers.

With the popularity of running in the 1970s, sports-specific shoes took off. The difference between the shoes for specific sports is not only how the shoe is made but how the shoes function too. For instance, a running shoe certainly needs to be constructed differently than one for wrestling. This allowed the shoe companies to offer a variety of shoes for different niche markets and expand the population to which they sell.

The starting point in discussing function is how the shoe fits. No matter how well the shoe is constructed, it will not function properly if it does not fit well.

There are some key factors to consider when considering the fit. Certainly measuring the foot and getting the length from heel to toe is important. This serves as a starting point when trying to find the right size shoe. Since shoe sizing is not standardized, sizing between manufacturers is not consistent. Generally, the difference between sizes is consistent with 1/2 sizes equal to 1/3″.

Once the overall length of the foot has been determined, the next measurement to consider is the arch length. This is the measurement from the heel to the ball of the foot. This is also known as the arch length. Arch length and foot length are not necessarily equal. A person can have a long arch and short toes or the opposite situation. Of the two measurements the arch length is actually the more important one. This measurement will determine how the foot fits inside of a shoe which in turn will determine how the shoe will function on the foot.

The ultimate goal is for the foot and the shoe to function together. For this to occur, the shoe needs to flex at the proper location. If the arch length is considered first, then this aspect of shoe fitting will be successful. If only the toe length is considered, then the foot might be placed either too far forward or too far back inside of the shoe. This would then prevent the shoe from flexing in the proper location.

The next consideration is the width of the foot which is measured at the ball region. There are different measurements that footwear manufacturers use for measuring width. There is the letter designation S, N, M, W, and WW as well as the traditional A, B, C, D, E, EE, EEE. Whichever width designation is used, each successive width expands the width of the shoe by one increment.

Although width needs to be considered when fitting the shoe, the volume of the foot needs to be considered as well. Feet that measure the same size can occupy different volumes inside of a shoe. The "thickness" of the foot from top to bottom or how much room the foot occupies inside of a shoe is an important factor in determining fit.

Once the measurements have been obtained, then the last of the shoe needs should be considered. The last that the shoe is made upon determines the shape of the shoe. Since feet come in many different shapes, there are a variety of shoes from which to pick. One shoe cannot be right for everyone. There are feet with a wide forefoot and those with a narrow heel. Lasts will exhibit certain characteristics that will be most suitable for specific foot structures. People often complain about having wide feet, but it is the narrow foot that is hardest to fit.

With hard to fit feet, customizing the fit is often necessary. For some, finding a shoe that fits can be a difficult proposition. Even after obtaining all of the measurements required and picking the shoe that appears to fit the best, the result still may not be as desired. That is when it is necessary to understand the art of shoe fitting so that simple changes can be made that will make the shoe work as well as it can.

These modifications include extra padding in the forefoot in order to snug up the front of the shoe and prevent heel slippage. Addition of tongue pads to enhance fit and alternative lacing patterns to either avoid problem areas on the foot or serve as a way to make the shoe stay on the foot better can also be very successful. Detailed lacing techniques are presented in Chap. 8. Fitting shoes is the first step to having a shoe function properly. The next step is to understand, in more detail, how a shoe functions and how it can either help an individual function better or even prevent injury.

Clinical Assessment of Athletic Shoes

Work is currently being done through the Shoe Review Committee of the American Academy of Podiatric Sports Medicine in order to quantify important characteristics of shoes to allow comparisons between shoes from different manufacturers.

For the purposes of this chapter, running shoes will be the focus. Running is the activity that is in common with most athletic activities and is also the activity which places high demands upon the foot. The standards assessed with running shoes are the ones that are adapted by other sports and then modified depending upon the sport and the specific demands that particular activity places upon the foot.

It is completely inadequate to recommend one shoe for everyone. That is the importance of coming up with standards by which to compare running shoes and the basis from which recommendations can be made for individual athletes.

Fit

The established standards start with the fit, but only in a broad sense. Fit is difficult to quantify because there is much subjectivity involved in how a person perceives the right fit. One person may prefer a tight fit, while another may prefer a looser fitting shoe. Therefore, in a broad sense, fit is quantified, but only by characteristics in the construction of the shoe and what the particular company offers in options. Some companies make one standard width for each size, but there are companies now offering additional widths. This is seen as a bonus as far as achieving the best fit possible. This way the shoe has a better chance of fitting the foot instead of getting the foot to fit the shoe. In the better quality shoes, not only is it just an additional width that is offered but it is how the shoes are constructed. In many shoes the same bottom is utilized for the different widths. In shoes with higher quality, each width is made on a different last meaning that the bottom will proportionally fit the upper. Therefore, a wider shoe is truly a wider shoe including the sole. For wide feet this is important because this will keep the foot from hanging over the sides of a sole that is too narrow.

Insoles

Removable insoles have become universal among running shoe manufacturers, which make replacing them very easy. Most of the insoles that come with shoes are only adequate at best, as they do not offer much in the way of additional cushioning and certainly don't offer much additional support. In fact, most serious runners are better off replacing the inserts that come with the shoes. This is also an area that can be utilized to help obtain better fit. Padding the insoles with additional cushioning can help absorb extra room inside a shoe that would be otherwise considered loose. Even modification of the insoles to relieve areas of pressure can be performed as well. If the individual wears custom orthotic devices, having the ability to remove the insole is very helpful. There is very little difference between shoe manufacturers regarding insoles. Refer to Chap. 9 for more insight on pre-fabricated insoles.

Forefoot Flexibility

This portion of the shoe is very important to assess. This will determine how well the foot and the shoe will function together. There is a very simple test in order to determine this characteristic. Bend the shoe while holding the heel and forefoot. The flex point of the shoe should match the flex point of the foot. The shoe, just like the foot, should bend at the ball of the foot. For optimal shoe and foot function, it is necessary for the foot and the shoe to work together. If the shoe bends anywhere but at the ball of the foot, this is not mechanically advantageous for the foot to function optimally. In shoes where the flex point is not in the proper location, the foot is forcing the shoe to bend thereby altering the function of the shoe and the foot.

Midfoot Sagittal Stability

This characteristic is similar to forefoot flexibility. Bending the shoe between your hands is the test to determine the sagittal stability. If the shoe bends in the middle instead of the ball of the foot, the shoe is considered to be poorly constructed and one that should not be recommended. There is a range within these characteristics though. It is not always absolute as to whether a shoe flexes or not. If there is a slight flex, that would be important to note versus one that is very flexible and a completely wrong location. The goal of all of these functional shoe characteristics is to provide the most optimal environment in which the foot will function. Characteristics that impair this goal are important to note and one should avoid recommending. Athletic shoes which improperly flex through the arch will increase the strain through structures such as the plantar fascia, peroneal tendons, and midfoot.

Midfoot Frontal Stability

This characteristic is similar to the previous two. However, instead of whether the shoe flexes up and down (in the sagittal plane), this characteristic assesses whether there is any torsional component to the flexibility within the shoe (frontal plane). If a particular foot is very flexible in the frontal plane meaning that there is a lot of inversion and eversion occurring, frontal stability of the shoe is important. If the shoe has poor frontal stability, then the shoe will not offer the stability required by the foot and injury risk may be increased.

Lateral Midsole Heel Cushion

Close inspection of the heel of the shoe is important. There are a few characteristics in this region to focus upon that will directly impact foot function. This is the location of the shoe that contacts the ground. Stability and cushioning in this portion of the shoe are critical in preventing injury and promoting proper function. Many shoes are constructed with the idea of trying to control motion within the foot at heel strike. Strategies involved in this area include midsole materials having multiple densities as well as different materials that respond to shock absorption better than others. When people try shoes on, one of the leading subjective perceptions people assess is cushioning. However, if the shoe is too soft this can present problems and actually contribute to injury in the foot or even the knee. Soft materials compress rapidly and accentuate excessive motion within the foot. A supinated heel strike, for instance, will become even more supinated if the shoe compresses too much or too quickly in this region. Therefore, softer is not necessarily better. It is important that the material chosen for the lateral midsole heel cushion is not too soft and not too compressible. Materials have been developed that are now being utilized that have shock absorption, but do not compress too rapidly. One can also note whether other strategies such as special shock absorption materials are employed in addition to the midsole material present.

Medial Midsole Heel Density

This is the opposite side of the shoe. Some shoes exhibit same density material both medially and laterally; for certain feet this may be adequate. But for those individuals that either need extra shock absorption or land in a highly supinated position, differing densities are often necessary. Just as with the lateral midsole heel cushion, the medial midsole heel density is important to note as far as compressibility as well. Certain materials will compress faster than others. This can be noted after a person has worn a shoe for a while. If the material wrinkles that means that it is unable to rebound from the repeated compression that occurs with each step. When assessing this portion of the shoe, one will note whether it is of uniform density between medial and lateral, a medium density, or high density which is a strategy utilized to limit excessive pronation during mid-stance.

Heel Counter

This is the portion of the shoe that wraps around the heel from medial to lateral within the upper of the shoe. Some shoes incorporate a firm material or even plastic in order to help contain the heel and eliminate extra motion. There are also shoes that do not pay any special attention to this portion. In these shoes, the upper is soft and flexible. If the foot has a tendency to either invert at heel strike or pronate excessively during mid-stance, the heel counter will do very little to eliminate the extra motion from occurring.

Outsole Surface Area

Looking at the shape of the bottom of the shoe will determine this particular characteristic. A shoe that has a sole as wide as the upper can be advantageous for extra support. If the sole tapers at the midfoot or even follows the contour of the arch, this can be a negative characteristic as far as providing support. The more surface area in contact with the ground the more support the shoe offers the foot.

Conclusion

Based on the shoe assessment characteristics, a point system was created in order to score shoes (see Table 14.3 in Chap. 14). The score that a shoe receives can be used to compare shoes from different manufacturers. It can also be used as a way to determine shoes that display certain important characteristics such as stability or motion control. If a shoe scores high in all categories, it is a stable shoe with maximum motion control. Not everyone needs this type of shoe though. Therefore, the point system can help decide where to start for the right shoe.

The shoe industry is a competitive one; styles and features of shoes constantly change because consumers desire new products. As a result, what sometimes seems like a great shoe or great feature of a shoe may disappear as fast as it came. Understanding the parts of a shoe and how to assess the function of shoes will help the sports medicine specialist keep abreast of the continually changing offerings that the shoe companies produce.

Athletic Shoe Fit, Modifications, and Prescriptions

6

Josh White and Arnie Davis

Whether treating the feet of professional athletes or weekend warriors, it is critical that patients wear shoes that correctly fit. Some foot care physicians fit patients with shoes themselves. Others prefer to refer patients to stores for others to decide what fits best. Either way, patients' needs are best served by the sports medicine specialist by assessing lower extremity functional biomechanics, identifying structural requirements, and creating a plan to achieve therapeutic objectives. There are four simple yet key considerations about athletic footwear, orthoses, and shoe modifications for achieving best

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clinical outcomes. Sports medicine professionals can best help their patients if they address the foot to shoe relationship with respect to “size, shape, stability, and style”.

Shoe Fitting

Size. Size is the first thing one usually considers when fitting shoes. Unfortunately, selecting the right shoe size can be difficult. There are no manufacturer standards for how length and width must measure. Variability in size exists between brands, among styles of a particular brand, and even within a particular style if manufactured by different factories.

Despite this inconsistency in shoe sizing, proper fitting best starts with some form of measuring (Fig. 6.1). It is best to then try on shoes that are made in three or four widths per half size and at a store with sufficient inventory to offer a wide variety of fitting choices. Unfortunately, most manufacturers make shoes in only one width and most stores carry limited inventory. This results in patients with wide feet frequently fit with shoes longer than needed to get the width they desire.

When shoes are correctly fit, there should be approximately ½″–5/8″ space between the end of the longest toe and the end of the shoe (Fig. 6.2). The shoe should be wide enough such that the foot does not bulge on the lateral side but not so wide that excess material can be pinched on top. Sometimes, after wearing shoes that fit short, the right size will feel too roomy. Generally, if shoes fit without slipping in the heel, then the bigger the size, the better.

Shape. It sounds simple enough, yet it is often overlooked how important it is to match the shape of the shoe to the shape of the foot (Fig. 6.3). Feet come in an infinite variety of shapes, yet shoes are mass produced using a limited number of forms called “lasts.” Lasts are designed to accommodate common foot characteristics including the

Fig. 6.1 Brannock Device shown being used for measuring foot metrics

Fig. 6.2 Checking the proper length of the shoe fit

Fig. 6.3 Foot shape shown matching shoe shape

breadth of the forefoot, arch morphology, instep height, toe depth, and heel width. Even if sized correctly, picking the wrong shoe shape will result in suboptimal shoe fit.

Most feet demonstrate a medium height arch, mild amount of in the transverse plane, and a broad forefoot. Such feet are best fit in shoes made on what is sometimes referred to as a “Universal” shaped last.

A segment of the athletic population has feet that demnstrate convexity in the transverse plane. Such feet are best fit with “Curved” shape lasts.

Feet that have low to flat arches require ample breadth in the midsection of the shoe. These feet are best accommodated with shoes made from what is sometimes referred to as “Linear” shape lasts.

Stability. Athletic shoe manufacturers promote stability in their marketing and promise such features as limitation of excessive foot motion to allowing feet to move as nature intended. They have developed a slew of design features to provide an appropriate combination of cushioning and control of foot motion. To determine a shoe’s stability, squeeze the sides of the heel counter, the rear part of the shoe. Stable shoes resist compression. Another test is to hold the shoe by the heel and at the toes and give it a twist. Torsionally stable shoes resist twisting; flexible shoes twist easily (Fig. 6.4).

The foot’s longitudinal arch helps absorb impact forces from heel strike to midstance. In the second half of the stance phase of gait, the arch normally rises, stabilizing the foot and helping it to propulse forward with an efficient, smooth gait. When the arch lowers following heel strike and rises again during the propulsive phase of gait, there is said to be biomechanically efficient gait and the foot itself is referred to

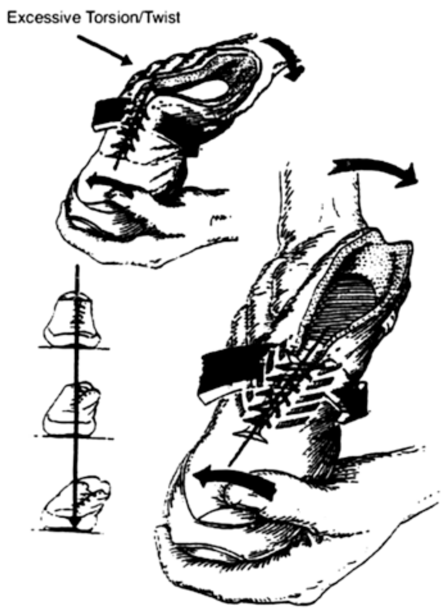

Fig. 6.4 Manually testing torsional shoe stability

as "Neutral." During walking and running, athletes with neutral type feet contact on the lateral side of the heel, the rearfoot everts, or rolls towards the medial side, then resupinates through the propulsive phase of gait. Old shoes worn by "neutral" feet generally reveal wear on the lateral side of the heel and then even wear across the ball, sometimes continuing to beneath the distal medial aspect.

"Neutral" shoes, recommended for "neutral" feet, such are cushioned and flexible enough to allow the foot to progress naturally through the gait cycle. Neutral shoes lack extra pronation control features which could injure biomechanically efficient runners by limiting needed foot motion.

Many athletes demonstrate mild to moderate overpronation. Immediately after heel contact, such feet evert beyond perpendicular. While it's beneficial that impact forces are dissipated by pronation following heel strike, excessive heel eversion can result in overuse injuries relating in strain to plantar-medial foot anatomy. "Stability" shoes are recommended for athletes who demonstrate moderate overpronation and

Fig. 6.5 Midsole features shown to affect varying degrees of "pronation control" of traditional running shoes

who have low to normal arches. Such athletes generally benefit from shoes that feature a combination of good support and midsole cushioning.

Athletic shoe manufacturers incorporate an assortment of features designed to support the medial aspect of the heel, prevent compression beneath the plantar medial aspect of the sole and thus limit rear foot pronation (Fig. 6.5).

When there's overpronation, after the lateral heel makes ground contact, the subtalar joint everts excessively, limiting shock absorbing benefits. Pes plano valgus feet make it difficult to run efficiently, frequently tire easily and are more subject to heel spurs, bunions, and medial knee pain. "Motion control shoes" are recommended for athletes with low arches who demonstrate moderate to severe overpronation, who need maximum rearfoot control and extra support on the medial side of their shoes. Supportive features include firm stabilization at the medial heel to limit heel eversion and a wider heel to provide stable support. This type shoe is also best for larger athletes who need support and durability.

Athletes with rigid, high arch feet that demonstrate minimum pronation are generally well suited for running fast but such feet offer limited shock absorption. These runners are usually midfoot or forefoot strikers and are more susceptible to impact injuries such as shin splints, stress fractures, and Achilles tendonitis. These athletes generally lack ankle joint dorsiflexion. Such feet are best accommodated in neutral-cushioned shoes as they feature maximum midsole cushioning and minimum medial support.

Style. There was a time when sneakers with canvas uppers and gum rubber soles were considered adequate for most any athletic activity. Today, shoes are manufactured for specific activities and surfaces using a slew of high-tech componentry (Fig. 6.6).

Running shoes are lightest in weight of any style and offer the greatest cushioning. They are designed for linear activity and should never be worn for any sort of court activity. Running shoes are acceptable to wear for walking but walking shoes should not be worn for running.

Athletic walking shoes are similar to running shoes but often feature leather in the upper, giving them greater durability and slightly heavier weight. Athletic walking shoes are also generally not as boldly designed, making them often more appropriate by many for everyday wear.

Tennis, basketball, and other court sports entail quick changes in direction. Court shoes must integrate superior medial and lateral forefoot support. Tennis also entails a lot of dragging the forefoot and so these shoes often feature extra durability in the big toe area.

Cross-training shoes vary in design; some are lighter in weight and similar to running shoes while others offer greater medial/lateral support and are are similar to court shoes. Light weight cross-trainers are okay for running up to 2–3 miles and fine for working out on exercise machines. For basketball, tennis, and other court activities, the heavier weight cross-trainer, generally made with leather, is better.

Fig. 6.6 Examples of the many varieties of shoe construction and technologies

Hiking requires support, protection from the environment, and durability. Such shoes offer heavier, more durable soles and generally come up higher on the foot to provide greater ankle support. It's desirable that they feature a waterproof lining and sealed seams.

The most important element of shoe fitting is ensuring that the shoes fit comfortably. It's best to take shoes for a test run. While some time for break-in to be anticipated, correctly fit shoes will generally feel good right away. Occasionally, when a person has been wearing shoes that fit too small for a long time, the correct size will feel excessively roomy. The patient should be encouraged to give the correct fit a try if there are no objective signs of looseness like slipping in the heel. Fairly soon, the athlete will appreciate that it is normal to be able to wiggle the toes in properly fit shoes and that feet should not ache by the end of the day.

Orthotic Prescription

Frequently, the best shoes do not provide all that is required in terms of support, cushioning, and protection. Foot orthoses offer a way to improve how shoes work, can improve athletic performance, and help athletes recuperate from injury.

Prefabricated Orthoses

Prefabricated or ready-made orthoses are carried in most good running shoe stores and by many foot care specialists. Designs run the gamut from thin cushions to durable, pathology-specific devices that mimic custom-made devices, but cost a fraction as much. Ready-made orthoses are most appropriate and most effective as a first-line treatment for conditions requiring a mild to moderate amount of additional support and/or cushioning (Fig. 6.7).

Cushioning can be provided with inserts as thin as 1/8″. The best combination of cushioning and durability is offered by neoprene foam, polyurethane, or silicon gels. Ball of the foot protection requires that the cushioning extend the full length of the shoes. Adding 1/8″ or more of cushioning generally requires the shoe in which the inset is worn to have a removable sock liner that can be replaced with the additional cushioning.

Some prefabricated orthoses offer a measure of support that approaches that provided by some custom devices. Such devices are good for persons with moderately excessive pronation who present with such conditions as plantar fasciitis, Achilles

Fig. 6.7 Examples of the many varieties of prefabricated orthoses

tendonitis, and shin splints. These devices are also sometimes effective at providing an immediate short-term benefit while waiting the several weeks that it takes for custom devices to be made.

Prefabricated orthoses that offer more substantial support often require a short period of time to feel completely comfortable. It's generally recommended that devices be worn just a couple of hours at first and then increase the wearing time an hour or two per day for the first week. Following the break-in period, the support of the orthoses should be barely felt but if they were to be removed from the shoes, a definite lack of support should be noticed.

It's essential to always let comfort be the guide. The expectation of wearing prefabricated or custom orthoses should be that there is greater comfort wearing the devices than when not.

Custom Orthoses

If ready-made orthoses fail to help, it may be advisable to utilize a custom-molded version. Some of the best reasons for trying custom-made orthoses include: failure of prefabricated devices to provide comfort/alleviate symptoms, accommodation of irregular foot shape, a desire to off weight plantar prominences, and to offer a superior level of pronatory control. The success of custom devices depends on both the skill of the practitioner in taking a negative impression and in the orthotic design. How the foot is positioned during casting/scanning significantly impacts the effectiveness of the device. In the case of pronatory control, the objective is to maintain

Fig. 6.8 Examples of the varieties of custom orthoses

the foot in a neutral position. This is only possible if the foot is accurately casted in the desired alignment (Fig. 6.8).

Features that can be integrated into a custom orthoses that can increase pronatory control include the rigidity of the shell material, the width of the device, the depth of the heel cup, the amount of arch fill used in the positive cast, and how the device is balanced. It is possible to reduce pressure on specific areas via padding and to create plantar accommodation by off-weighting specific areas on the bottom of the foot.

Athletic Shoe Modifications

There are biomechanical conditions that require more than can be addressed with a combination of shoes and orthoses. One leg may be shorter than the other, there may be significant plantar pressure or no shoe may fit just right.

Limb length discrepancy (LLD) may be the result of a congenital problem or from an accident. While limb length is measured in several different ways, anterior superior iliac spine (ASIS) to the ground, ASIS to the medial malleolus, using a level and via X-ray, the best way to determine the appropriate amount of *lift* to add utilizes none of these methods. People compensate for LLD in different ways. The best was of determining how much lift to add is subjective, determined through trial and error by adding varying amounts of lift beneath the heel and forefoot. The right amount of lift will create a feeling of balance such that the patient does not feel as though he/she is balanced towards the right, left, front, or back.

Generally, it is desirable to add as much lift as is possible to the inside of the shoe. The thickness of lift that can be comfortably added depends on the shoe style. A tassel loafer may only allow ¼″ beneath the heel while high top athletic shoes may allow the addition of as much as a full inch. If additional lift is required beyond that which fits inside the shoe, it needs to be added outside as an external shoe modification (Fig. 6.9).

The first way to relieve pressure beneath a submetatarsal prominence is via an orthotic forefoot accommodation. Additional pressure can be relieved by *carving out the midsole*, from the inside of the shoe, specifically beneath the high pressure area. The specific location can be determined by marking the area of the foot with some lipstick and carefully placing the foot, without a sock, into the shoe, all the while taking care not to smudge the marking before it gets to the proper place in the shoe.

Rocker bottoms offer an effective way to both relieve submetatarsal pressure and provide sagittal plane motion where such motion in the ankle, subtalar, midtarsal, and/or metatarsophalangeal joints may be limited (Fig. 6.13). Rocker bottom soles are created by adding increased thickness to the shoe midsole beneath the heel, beneath the ball, and then tapering it to the toes. A typical thickness is ½″. The rocker bottom allows the shoe to roll forward, maintaining a normal pattern of gait, without requiring sagittal plane dorsiflexion of the foot. It can limit motion when such motion is painful and compensate for a lack of motion when joint motion is

Fig. 6.9 External shoe modifications shown

External lift for limb length discrepancy

Lateral flaring

restricted. In the absence of a LLD, whatever thickness rocker bottom that is added to one shoe should be added to the other.

Stretching. Stretching is beneficial when a foot is irregularly shaped causing shoes to fit correctly in all but a specific area. The ball and ring stretcher is effective for spot stretching over a bunion or dorsally over hammertoes (Fig. 6.12). The

Fig. 6.10 Custom modifications to midsole and outsole

Fig. 6.11 Two-way type shoe stretcher shown

Fig. 6.12 Ball and ring shoe stretcher shown

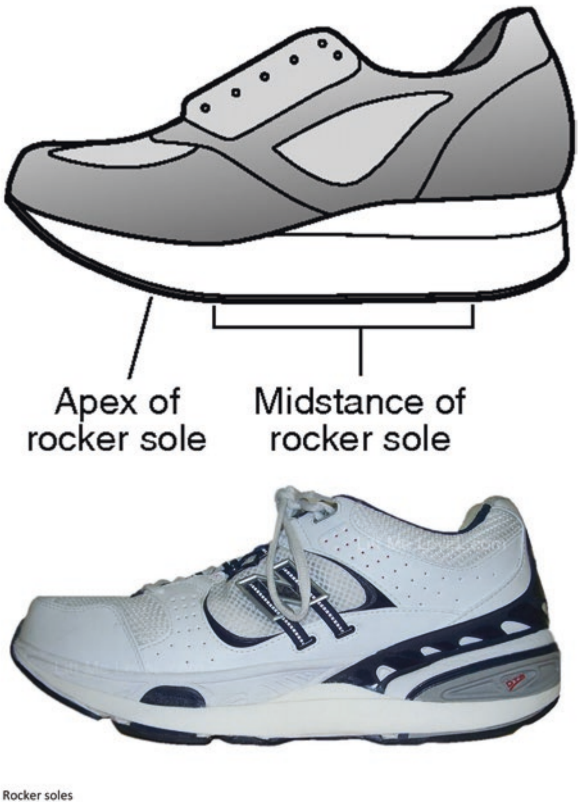

Fig. 6.13 Features of a rocker sole

two-way type stretcher is better for creating width across the entire forefoot (Fig. 6.11).

Flaring. Ankle inversion and excessive pronation can be limited by widening the outsole of the shoe either laterally or medially. While possible to add soling material such as EVA to the medial or lateral rear quarter, a better looking approach entails splitting the outsole and inserting midsole material to create the requisite medial or lateral width (Fig. 6.10).

These simple guidelines will help sports medicine practitioners address most common shoe fitting issues and frequently seen foot pathology. Such an approach will help injuries to be prevented, patients to heal faster, and enable patients to more fully participate in athletic activities.

Sample Prescriptions

Dx: Plantar fasciitis, heel pain

Rx: Prefabricated heel cups, Viscoelastic heel pad. Provide calcaneal cushioning. Posted version can offer some small measure of calcaneal control.

Dx: Achilles tendonitis

Rx: ¼″ heel lift to take tension off of Achilles tendon that demonstrates limitation of ankle joint dorsiflexion. If Achilles tendonitis is related to excessive pronation and not limited dorsiflexion, modalities to limit subtalar pronation are most appropriate. These include supportive prefabricated orthoses, custom orthoses and motion control type athletic shoes.

Dx: Pes planus

Rx: Firm prefabricated insert, possibly posted. Motion control type athletic shoe. Custom-molded orthotic device if superior support is desired.

Dx: Bunions

Rx: Shoe with broad forefoot. Stretching using either ball and ring device or a forefoot stretcher necessary if width of feet is asymmetrical or if fitting shoe wide enough in the forefoot results in slippage in the heel. Avoid upper patterns that place seams over the bunion area. There are also cushioned pads that can slip over the big toe and cushion the medial aspect of the first metatarsal head.

Dx: Neuromas

Rx: First consideration is to avoid compression across the forefoot. That means ensuring that the shoes are as wide as the foot and do not allow the foot to overhang on the sides. Often neuromas are associated with excessive pronation and so a supportive prefabricated insert and motion control shoe are appropriate. For greater relief, select an insert, either prefabricated or custom that features a metatarsal raise to spread out the metatarsal bones and lessen compression on the inflamed nerve.

Dx: Shin splints

Rx: May be the result of either a lack of ankle joint dorsiflexion secondary to tight Achilles tendon. Would be helped with 1/4″ heel lifts. If secondary to excessive pronation, motion control shoe and supportive prefabricated or custom orthosis.

Dx: Chondromalacia
Rx: Generally related to excessive subtalar joint pronation causing strain on the medial aspect of the knee and resulting in inflammation on the posterior aspect of the patella. Requires pronatory control via a supportive prefabricated or custom orthotic and motion control shoe.
Dx: Recurrent ankle sprains
Rx: Select shoe with wide lateral flare on outsole. Shoes should be broad in midfoot and demonstrate good torsional stability. They are a variety of prefabricated ankle supports that offer differing amounts of frontal plane control while allowing the ankle to move in the sagittal plane.
Dx: Hallux limitus
Rx: If related to excessive pronation, control foot motion with combination of prefabricated or custom orthotic device. A forefoot modification call a reverse Morton's extension sometimes can enhance first MTJ range of motion. If sagittal motion is limited secondary to osseous changes, the only way to improve mobility and maintain normal pattern of gait is via rocker bottom sole.
Dx: Intractable plantar keratosis
Rx: Submetatarsal pressure may be exacerbated by excessive pronation increasing pressure beneath first and or second metatarsal heads. First thing is to control pronation. Relief of pressure beneath met head can be accomplished via accommodation of a custom orthotic deice. Additional pressure may be relieve via excavation of the midsole. Rocker bottom soles can be beneficial if there is normal ambulation with metatarsal plantar flexion during the propulsive phase of gait.
Dx: Corns
Rx: Must relieve pressure on dorsal aspect of foot. Shoe must have adequate depth and best if made of soft, accommodative material. Ball and ring stretcher can relieve pressure over specific point on foot.
Dx: Edema
Rx: One of the toughest shoe fitting challenges as foot size fluctuates. It is most important to wear compressive socks. Socks should extend up the calf to control fluid accumulation. Shoe must allow adjustability of size. This is possible with laces that extend low on the foot and upper patterns that open to the sides. Stretchable materials make shoes more accommodating. It is best to use shoes that feature removable spacers that can be removed when foot swells and inserted when foot reduces in size.
Dx: Hammer toes
Rx: If flexible, a prefabricated or custom orthotic that features a metatarsal raise can sometimes cause toes to extend. If not, same as treating corns. Must provide adequate depth in shoe either via shoe shape and/or via spots stretching using ball and ring stretcher. There are also cushioned pads made of silicon that can be placed over the contracted joint to reduce pressure buildup.
Dx: Neuropathy

Rx: Most important that shoes fit properly. Cannot rely on patient feeling of fit to determine if shoes sized appropriately. Ensure that there is ½″ space between the end of the longest toe and the end of the shoe. Also ensure that patient wears cushioned socks, that the shoe is as wide as the forefoot and does not hang over the sides. A semi-rigid or cushioned orthosis helps control excessive pronation, provide additional shock absorption and creates maximal surface area between the foot and the ground. This is the most effective way to maximally distribute ground reactive forces. Patients must be educated to inspect their feet daily for signs of pressure including redness, calluses and blisters, the first indicators that an ulcer may be developing. Even ideally fit shoes can result in problems as feet can change, shoes wear out and objects can fall into shoes.

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Athletic Socks

7

Doug H. Richie Jr.

Introduction

Socks are an essential component of footwear for the athlete. Previously considered a commodity item, athletic socks are now designed to provide significant functional and protective benefits for the active person. This chapter will provide an overview of the key factors in the recommendation of proper socks (hosiery) for the athlete.

Historical Background

The concept of "sport-specific socks" emerged during the 1970s from the invention of the roll top sock, by James Throneburg, owner of ThorLo hosiery company [1]. Early patented designs from ThorLo placed extra padding in strategic locations of a sock to provide protection during running, tennis, skiing, and cycling. Over the next 30 years, numerous manufacturers have emerged, offering a myriad of designs for virtually every sport where shoes are worn. In some cases, the use of a sport-specific sock is valid, while many models and designs have questionable unique function.

Considerable research has also been conducted on specialized sports hosiery to determine physiologic benefits. This research has suggested that athletic socks can provide significant reduction of plantar pressures [2–5], reduced impact shock [6], reduced incidence of friction blisters [7, 8], and reduced symptoms of venous insufficiency [9, 10]. These medical benefits, validated by scientific study, gave rise to a new category of socks known as therapeutic hosiery, designed for patients with diabetes and arthritis.

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Basic Sock Design and Construction

Depending on the height of the upper or "foot" portion of the hosiery, an athletic sock has a specific description and sports application (see Fig. 7.1). An **over-the-calf** design is used for skiing, baseball, and soccer. A **crew length** sock is a standard athletic sock with universal applications. The upper of the crew sock ends just below the calf muscle. The **mini-crew** design ends just above the malleoli of the ankle and is a popular for running and tennis. The **roll top** sock ends at the topline of the shoe and is popular in golf.

The construction of an athletic sock can vary significantly among manufacturers. Depending on the type of knitting machine, a sock can have very dense "terry loop" pads or can have a flat knit design. The gauge of the knitting needle will determine the density of fabric within the sock. In general, more expensive socks utilize more fabric and tightly woven knit patterns in their construction to provide maximum protection for the foot.

The anatomy of an athletic sock provides further insight into design variations for the athlete. The "leg" or upper portion of the sock can vary in terms of overall compression and elasticity. This portion of the sock can have specialized padding or panels which are sport specific, such as shin pad for alpine skiing. Some manufacturers utilize specialized fibers in the leg portion of the sock to provide a wicking gradient to pull moisture out of the shoe.

Fig. 7.1 Example of sock designs. (**a**) Over-the-calf, (**b**) crew, (**c**) mini-crew, (**d**) roll top

The heel of the sock can be absent, as found in a “tube” sock, or can have a standard heel “gore” which provides a pocket for the heel bone. A “Y-Gore” provides the best fit and conformity for the heel. Tube socks do not provide adequate fit requirements for vigorous sport activity.

The “foot” of the sock can have a cushioned “sole” portion and cushioned “instep” portion, or some variation thereof. The arch section may have additional elastic for support. The toe area of the sock will have a seam which may be almost imperceptible in finer quality hosiery. So-called “seamless” socks are preferred for medical application but this feature may have benefit in reducing pressure over the toes in the active athlete.

A recent trend has been the offering of sport socks shaped specifically for the “right and left” feet. These socks have a tapered toe area to more closely match the parabolic shape of the forefoot. This may have an advantage in preventing “bunching” of excessive fabric in the lateral aspect of the toes.

Fiber Composition

One of the primary differentiating features of athletic socks, compared to dress/casual hosiery, is the utilization of high-tech fibers and yarns. Today, the ordinary white cotton “sweat sock” has been replaced with sport-specific socks composed of synthetic fibers designed to provide better comfort and protection for the feet of the active athlete. Research has shown that synthetic fibers can keep the feet drier, cushion the foot better, and provide better performance than traditional cotton fibers.

Moisture Management

With regard to moisture management on the surface of the foot, the terms “hydrophobic” (repel moisture) and “hydrophilic” (retain moisture) are utilized in describing sock fiber performance. In general, cotton fibers and most wool fibers are considered hydrophilic, while synthetic fibers are hydrophobic. The response of socks to exposure to moisture is important from both a comfort and clinical standpoint.

Moisture can accumulate in the shoe of the athlete from three different sources: the foot itself, the legs and trunk of the athlete, and the outside environment. The foot contains eccrine sweat glands which are innervated by cholinergic fibers activated by the sympathetic nervous system. The palms and soles are unique in having the highest density of eccrine sweat glands in the body: 2000 glands/cm^2, compared to a density of only 100 glands/cm^2 in the rest of the body [11].

The production of moisture from the sweat glands of the feet during vigorous physical activity is estimated to be as much as 200 cm^3/h [12]. The production of moisture from the remainder of the body during exercise can exceed 1 L/h [12]. The sum total of moisture potentially collecting in the shoe of the athlete during exercise will quickly exceed the absorptive capacity of any sock. Therefore, in order to keep moisture content at a minimal level on the surface of the foot during exercise, a sock must “move” moisture away to the shoe upper for evaporation. This process is known as wicking [13].

Cotton fibers are hydrophilic and absorb three times the moisture as synthetic acrylic fibers which are commonly used in athletic hosiery [14]. Once wet, cotton socks retain moisture and have a tenfold greater drying time compared to synthetic fiber socks [15]. In sedentary activity, cotton socks may be preferable to acrylic socks, given the low moisture output of the feet, and the better absorptive capacity of these hydrophilic fibers.

However, during vigorous activity, the absorptive capacity of any sock will be exceeded, and only a wicking gradient will allow movement of moisture from the foot surface to the shoe for evaporation to the outside environment. Hydrophilic fibers such as cotton have a 2.4 times greater resistance to moisture transport [15]. This may be related to absorption of fluid and swelling within the fibers themselves. When wet, acrylic fibers swell 5% while wool fibers swell 35% and cotton fibers swell 45% [16]. Swelling of fibers is related also to a loss of shape and conformability to the foot. Cotton socks tend to bunch and elongate when wet, while synthetic fiber socks are more likely to retain shape, cushion, and resiliency in these conditions.

While wicking properties of sock fibers vary considerably, the ability of a sock to keep the surface of the foot dry relies on several variables. In an athletic shoe, there may be less resistance to moisture transport and evaporation thru the upper material, a high top boot such as worn during hiking or worn by military personnel will not allow evacuation of moisture to the outside environment. This was shown in a study by Bogerd et al. where moisture levels were measured on the feet of soldiers after marching 6.5 km in standard military boots [17]. Socks composed of a blend of 50% Merino wool and 33% polypropylene kept the surface of the foot drier than socks composed of 99% of polypropylene. According to previous research, polypropylene would be expected to wick better than wool [18]. However, the wool/polypropylene blended socks absorbed more moisture than the pure polypropylene socks and also kept the surface of the foot drier in marching soldiers wearing military boots. When the footwear does not permit evacuation of moisture to the outside environment, absorption rather than wicking may be the desirable feature of sock fiber composition.

Fibers Used for Athletic Socks

The common fibers used in the manufacture of specialized athletic hosiery are listed in Table 7.1. The majority of fibers used in the construction of athletic hosiery are from synthetic sources. This is because synthetic fibers have been engineered to have physical properties which are desirable for athletic performance: water resistance, wicking, thermal insulation, wind resistance, antimicrobial resistance, reduced weight, cushion and resiliency, and reduced coefficient of friction. Other important features of athletic socks include durability, maintenance of shape when

Table 7.1 Fibers used in sock construction

	Brand names	Manufacturer
Merino wool		
Acrylic	Duraspun	Solutia, Inc.
	Cresloft	Sterling Fibers, Inc.
	Microsupreme	Sterling Fibers, Inc.
Polyester		
	Coolmax	INVISTA, Wichita Kansas
	ComFortrel XP	Wellman, Inc.
	Sensura	Wellman, Inc.
	Spunnaire	Wellman, Inc.
Polypropylene		
	Innova	American Fibers and Yarns
Insulating		
	Thermolite	INVISTA
	Hollofiber	Wellman, Inc.
	Outlast	
	X-static	Noble Technologies
Antimicrobial		
	X-static	Noble Technologies
	Microsafe	Celanase
	Biofresh	Sterling Fibers, Inc.

http://www.fabriclink.com/search/fiber-search.cfm
http://www.fabriclink.com/Presentations/index.cfm?ID=68 (X-static link)
http://www.fabriclink.com/Presentations/index.cfm?ID=13 (Innova)
http://www.fabriclink.com/Presentations/index.cfm?ID=27 (Comfortrel)
http://www.invista.com/page_product_coolmax_en.shtml (Coolmax)
http://www.invista.com/page_product_thermolite_en.shtml (Thermolite) replaces Thermax
http://www.foxsox.com/SockTechnology/Index.aspx#FiberTech (Fox River)

wet, machine washable, quick drying, and odor resistance. Although cotton fiber socks do not fulfill these functions, other natural fibers may perform just as well as some synthetic fibers.

Wool, being a natural fiber, is hydrophilic but may not have all of the undesirable features of cotton fibers when used for high performance sock construction. Specialized wool yarns known as Merino Wool have been developed which have many of the characteristics of synthetic fibers. Compared to traditional wool, Merino wool has a much finer core diameter of each fiber, giving a softer feel and more air space for moisture movement. Merino wool has fewer tendencies for skin "itch" which is common with regular wool socks and apparel. The finer fiber and natural air spaces created by Merino wool have lead manufacturers to claim that this fiber is superior to any synthetic fiber for insulation and wicking.

The most popular synthetic fibers utilized in athletic hosiery are acrylic and polyester. Both acrylic and polyester fibers are hydrophobic and have superior wicking properties and reduced drying time than cotton. Coolmax fibers have a four-channel geometric configuration to enhance surface area and moisture movement. As a result, studies have shown that Coolmax and other polyester fibers have a 15% faster drying time compared to acrylic fibers. Both acrylic and polyester remain soft with multiple machine washings, resist wrinkles and stains, and retain their shape with moisture exposure. One shortcoming of acrylic is poor insulation. On hot surfaces in summer months, acrylic fiber socks can conduct heat and be undesirable. Hollow core polyester or Coolmax socks may be preferred in these conditions.

Insulating fibers have been developed for cold climate sporting conditions. Thermolite and Hollofil are examples of hollow core fibers designed to trap air and provide an insulating layer for trapping heat against the skin of the foot. Wool fibers have this same "air-trapping" framework which has made wool a fiber of choice for cold climates for decades. Newer fibers such as Outlast have a chemical property to store and release heat, depending upon the skin temperature. Silver impregnated X-static fibers have a natural heat retaining capacity. X-static claims that 95% of body heat is reflected back to the skin by the silver fibers within the sock.

X-static is also one of the newer types of sock fibers which have antimicrobial properties. Other fibers marketed with antimicrobial claims include Microsafe, Innova, Cupron, and Biofresh. The benefits of antimicrobial fibers for sock construction are discussed later.

Clinical Benefits of Athletic Socks

Being the closest layer of protection against the foot, hosiery has the potential to protect the skin and the deeper tissues from injury. While most clinicians intuitively examine the role of shoes and orthoses as a cause and preventive mechanism for injury, few look at the role of hosiery in this important area of sports medicine.

In walking and running, the primary stresses on the feet are impact, plantar pressure, friction, and shear [19]. Impact forces result from gravity and inertia as the body propels forward. Plantar pressures are the result of impact, bone deformity, and biomechanical issues. Friction and shear occur when the foot strikes the ground tangential to the supportive surface. Friction and shear also occur when the foot pushes off in propulsion. Frictional forces oppose movement of the skin against the supportive surface [20].

When external movement exceeds the frictional force at the skin interface, shear occurs where layers of skin begin to move upon each other. Initially, shear forces cause exfoliation of the stratum corneum on the skin surface [21]. In the palms of the hands and in the soles of the feet, the integument has a thick stratum corneum and stratum granulosum held tightly to the deeper layers. When high frictional forces secure the surface of the skin to the supportive surface, continued shearing forces can cause a movement interface between the stratum granulosum and the stratum spinosum causing a cleft to develop, resulting in a friction blister [22].

Over the past 15 years research has shown that specialized hosiery can significantly reduce impact shock and plantar pressures on the foot. In addition, there is indirect evidence that specialized hosiery systems can mitigate shearing forces which result in friction blisters.

Impact and Pressure Reduction

During walking and running impact shock occurs over a relatively short period of time as ground reaction forces are transmitted into the foot and then dissipated throughout the body [23]. Impact shock has been attributed to be a contributing factor to a wide range of pathologies including degenerative joint disease, soft tissue injuries and low back pain, plantar fasciitis and Achilles tendinitis [24].

Artificial shock absorbers such as footwear and insoles have been studied to determine ability to protect the body from impact stress [25, 26]. More recently, researchers have begun studying the potential of specialized hosiery products to attenuate shock and provide benefit in the reduction of impact-related injuries.

Howarth and Rome studied five different sock constructions to determine if any reduction of impact shock could be measured during treadmill walking [27]. A wool cushion sole sock as well as an acrylic cushion sole sock significantly reduced impact shock compared to either a standard cotton sock, double-layer cotton sock, and a cotton sock with a terry pile weave. The authors concluded that certain fibers such as wool and acrylic are better suited to reduce impact shock as long as denser padding is provided in a cushion sole construction.

Blackmore et al. used an impact testing system which simulated heel strike forces during running to measure the reduction in impact shock provided by socks and shoes [28]. Eight different sock designs demonstrated a reduction of peak impact force by up to 20%, a delay in onset of loading by up to 33% and a reduction of loading rate by up to 47%. Reductions in impact shock also occurred with the sock-shoe condition, but to a lesser degree owing to the superior cushioning effect of the shoe alone. The sock which achieved the best shock attenuation had the thickest construction and was composed primarily of Merino wool. The researchers concluded that socks composed primarily of cotton fibers have the least capacity for reducing impact shock and plantar pressure.

Plantar pressure measurements study the foot-ground interface and can provide insight into the role of hosiery to protect the integument and underlying skeletal structures of the foot. Veves et al. conducted several studies of plantar pressure dissipation during barefoot walking on an optimal pedobarograph of specialized padded (ThorLo) hosiery. These densely padded socks showed a 30% reduction of peak plantar pressures during walking in diabetic patients with peripheral neuropathy. Less padded, sport socks also demonstrated significant pressure reduction of 15% which was maintained after 6 months of continuous use [3].

Donaghue et al. also studied padded (ThorLo) hosiery using in-shoe pressure measurements on diabetic patients [4]. Padded hosiery demonstrated a significant 10.7% reduction of peak plantar pressure inside the shoe when padded hosiery was compared to conventional socks. More recently, Garrow et al. utilized in-shoe pressure testing of specialized double-layer acrylic hosiery in diabetic patients [5]. A 10.2% reduction of peak forefoot pressure was measured compared to conventional socks.

Friction Blisters

Studies of friction blisters and hosiery utilized subjects more representative of athletic patients rather than diabetic subjects with neuropathy. Friction blisters are considered the most common skin injury in sport [29]. Because the sequela of these blisters can result in infection and disability, the subject of blister prevention has been of keen interest particularly in the United States Military.

Herring and Richie conducted a prospective, randomized cross-over study of 35 long-distance runners wearing padded socks composed of either acrylic fibers or cotton fibers [7]. The runners wearing acrylic socks experienced half as many blisters as those wearing cotton socks. The subjects wearing acrylic fiber socks perceived that their feet were dryer compared to wearing cotton socks. Previous studies had shown that moisture content on the skin surface increased frictional force and tendency to form blisters.

Herring and Richie conducted a similar study comparing acrylic fiber socks to cotton socks, but utilized a less padded thinner sock compared to their original study [8]. The superiority of either fiber to reduce blisters could not be demonstrated with non-cushioned socks, leading the researchers to conclude that both construction and fiber composition were important in a sock's ability to prevent friction blisters.

Knapik et al. studied 357 U.S. Marine recruits during 12 weeks of basic training to determine the rates of blister formation in the feet while wearing one of three types of sock systems [30]. The use of a polyester (Coolmax®) liner combined with a heavily padded wool/polypropylene blended outer sock resulted in the lowest incidence of blisters compared to the single-layer standard wool sock (40% incidence vs. 69%). Adding a Coolmax® liner to the standard wool sock reduced sick call visits (24.9% standard vs. 9.4% standard with liner).

Other studies of marching soldiers in the U.S. military have confirmed the superiority of synthetic fiber socks, particularly when used as a liner inside of a more heavily padded sock [31, 32]. Double-layer synthetic sock systems have been shown to be more effective than single-layer synthetic fiber socks in the prevention of blisters [32–35].

Studies of socks and friction blisters on the feet suggest that the establishment of a movement interface either within the sock itself or between the layers of a sock system will prevent skin injury. Furthermore, reducing the friction force on the skin surface itself may be dependent upon the fiber composition of the sock, where synthetic fibers appear to work best [36, 37].

Potential Clinical Benefits

Research on newer padded or double-layer socks systems have revealed significant benefits which have direct relevance to the active athlete [17, 37]. Certain socks appear to be able to reduce moisture content on the feet during activity which has direct benefit from both a comfort and skin injury standpoint. Reduced moisture content of the skin of the feet during vigorous activity will minimize the chance of friction blisters. Damaging skin shear will also be minimized when thicker padded socks are worn, or when a two-layer synthetic sock system is worn. Other skin injuries such as calluses, corns, and toenail trauma may also be minimized by the wearing of proper socks.

While shoes and foot orthoses are commonly regarded as the major protection of the feet of the athlete, hosiery has been demonstrated to provide additional protection from impact and pressure which are attributed to be a cause of many foot injuries during running and jumping. Reduction of impact and plantar pressure on the feet can be expected to minimize the risk of common foot injuries such as capsulitis, bursitis, heel bruise, and stress fractures.

Hosiery and Skin Infections

The warm damp environment of athletic footwear is a breeding ground for microorganisms. The athletic sock can be both a barrier and a transmission vehicle for infection of the foot from the shoe or reinfection from the foot itself [38]. Until recently, the role of the athletic sock in the propagation or the treatment of skin infections has not been well understood.

Tinea pedis and onychomycosis are the most common skin infections seen in running athletes [39]. It has now been well established that the common dermatophytes causing these infections, *Trichophyton rubrum and Trichophyton mentagrophytes* can survive for long time periods in athletic socks worn by infected users [40].

A study has been published which validates previous speculation that socks could harbor fungal pathogens and contribute to reinfection during treatment. Amichai and coworkers cultured sections of socks worn by 81 patients treated for tinea pedis and onychomycosis [41]. All of the patient's feet had been confirmed infected, showing positive culture with *Trichophyton rubrum*. All of the cultured samples taken from the socks worn by the patients contained microorganisms . Over 50% of the sock samples from the patients contained *Trichophyton rubrum and Trichophyton mentagrophytes*. What is most interesting is what happened after these socks were cleaned in a standard domestic washing machine.

When the contaminated socks worn by patients with tinea pedis and onychomycosis were laundered in a domestic washing machine at 40 °C, 36% of the socks revealed positive fungal cultures at the end of the cleaning and drying cycle [41]. When the contaminated socks were washed at 60 °C, only 6% tested positive for fungus, all with *Aspergillus* species. *T. rubrum* was essentially eliminated with laundering at 60 degrees water temperature.

Hammer et al. studied the propagation of fungal dermatophytes before and during domestic laundering of hosiery [40]. In the first phase of this study, it was shown that socks containing *Trichophyton rubrum* and *Candida albicans* could contaminate other laundry stored in the same clothes basket. Ten percent of clean or sterile laundry specimens stored in contact with contaminated sock specimens for 1 h became contaminated which was verified by positive fungal culture results. When the contaminated socks were laundered at 30 °C with detergent bleaching agents, over 50% of the socks demonstrated positive culture for *Trichophyton rubrum* after washing. Increasing the temperature to 60 °C effectively eradicated all of the *Trichophyton rubrum. Candida albicans* was eliminated at both washing temperatures.

Hammer et al. also found that while washing at 30 °C, 16% of the initial spore load of *T. rubrum* from the contaminated socks was found in the rinse water of the washing machine. They speculated that this rinse water could effectively contaminate all of the textiles in the washing machine which were mixed with the socks worn by fungus-infected patients.

Even if we wash our socks separately, they may not always end up free of fungus even if they are washed according to our standard tradition. To drive home this point, a study of patients who were being treated for onychomycosis and tinea pedis at a dermatology clinic were asked to bring in a pair of "clean" freshly laundered socks for examination [42]. Fungal contamination with *T. rubrum* confirmed with culture was found in 10% of the laundered socks, indicating that exposure to the fungus would continue in those patients who washed their socks with traditional protocol.

These findings may justify the wearing of hosiery containing antimicrobial fibers to counteract the potential for reinfection during fungal treatment. Indeed socks containing fibers impregnated with copper or silver have gained popularity [43, 44]. At least one study has shown positive effects treating tinea pedis in patients using copper impregnated socks [45]. More studies are needed to validate any clinical benefits of metallic ion impregnated socks to reduce the risk of infection in the feet of the user.

Microencapsulization of pharmaceutical agents which are incorporated into sock fibers has received interest [46]. The content of the capsules can be released from the sock surface by friction, pressure, or change of temperature. Antifungal drug microcapsules have been applied to socks and have been studied for treatment of patients with tinea pedis [47]. Long-term studies are needed to verify the efficacy and safety of this new form of sock therapy.

Compression Hosiery in Sport

Compression stockings have long been used to treat chronic venous insufficiency. Previously, researchers recognized the potential of over-the-calf sport socks designed for basketball which could also provide improvement of venous insufficiency for older patients [9].

Since that time, sport socks have been modified to provide compression to the legs to provide anticipated improvement of performance and recovery from performance [48]. The initial goal of compression therapy during sporting activity was to improve venous return with the possibility of improved blood flow to muscles [49]. Other researchers speculated that mechanical compression could reduce muscle damage and enhance recovery from training and exertion [50]. However, studies verifying these benefits for athletes wearing compression socks have shown conflicting results.

Compression stockings have shown benefit in reducing post exercise soreness while improving post exercise muscle function [51, 52]. In contrast, compression stockings did not reduce muscle soreness after running and did not reduce blood markers for muscle damage after repeated squats [53, 54]. While these laboratory studies provide some insight into physiologic benefits of compression stockings, studies of athletes in actual competition may provide better insight and understanding.

A study of 36 athletes competing in a half-ironman triathlon competition showed no advantage of wearing graduated compression socks in terms of prevention of lower limb muscle function or reduction of post-race blood concentrations of myoglobin and creatine kinase. The researchers concluded that compression stockings were ineffective for averting muscle fatigue and muscle damage during triathlon events [55].

The role of compression stockings in the recovery from running a marathon race was studied in 24 subjects who were randomized into a treatment group and a sham group [56]. Perceived muscle soreness was significantly lower in the group who wore compression stockings immediately after the race and for the following 72 h. However, there was no improvement of muscular strength or blood markers of exercise-induced muscle damage.

Another study focused on the use of compression stockings during the actually running of a marathon race. Seventeen runners wearing graduated compression socks were compared to 17 runners who wore conventional socks. The use of compression stockings did not improve running pace, did not affect post-race muscle power, and did not prevent exercise-induced muscle damage during the marathon. The authors concluded that wearing compression stockings during long-distance running events is an ineffective strategy to avoid the deleterious effects of muscle damage on running performance [57].

Conclusion and Recommendations

When recommending socks for an athlete, it should be recognized that specialized athletic hosiery may change the fitting requirements of the shoe. Heavily padded sports-specific socks may require the addition of a full shoe size to allow proper room for the foot. Therefore, the selection of athletic socks should occur during the measurement and fitting process when athletic shoes are being purchased. The feet should be measured when the athlete is wearing the specialized socks which will be worn during the sport.

Narrow feet may benefit from specially designed socks for the right and left feet. Such socks may prevent bunching of excessive fabric over the lateral toes. Conformed fit is difficult when socks are offered in sizes covering a broad range (greater than three shoe sizes). Premium sport socks are usually offered in narrow size ranges which more accurately fit the foot. It should be recognized that sock sizes are not the same as shoe sizes: manufacturers may list the sock size, the shoe size, or both.

Certain socks may be recommended depending upon the clinical history or needs of the athlete. In the case of chronic blisters, a double-layer or padded hosiery system is recommended. If there is no significant concern about skin injury, the selection of fiber may be more important than construction style. Acrylic fiber socks are the most versatile of all athletic socks and make a good general sock recommendation. Depending on anticipated exposure to temperature extremes, hollow fiber or wool socks may be indicated.

Finally, the athletic hosiery marketplace is filled with products with consumer benefit claims which have not been substantiated. Many times, promises of blister protection, antimicrobial protection, and insulation have not been proven with adequate scientific study. Furthermore, the true value of a "sport-specific" sock may only be in the packaging rather than in a specific unique construction designed for the activity.

Based upon the best available scientific evidence, the following conclusions and recommendations regarding athletic socks can be made:

1. Cotton fibers are not recommended for construction and use in athletic socks because of poor performance when exposed to moisture.
2. Synthetic fibers are superior to cotton in providing better wicking of moisture from the skin surface of the foot, faster drying time, better maintenance of shape when wet, better durability with multiple machine washing cycles.
3. Wool fiber socks, particularly specialized Merino Wool have many positive characteristics of synthetic fibers. Wool fiber socks are superior in cold environments and appear to have adequate wicking capacity to keep the feet drying than cotton fibers.
4. Padded hosiery products are preferred to thin, un-padded socks because padding can protect the skin surface from friction and shear. Padded socks also can significantly reduce plantar pressures and impact shock which may reduce the risk of musculoskeletal trauma to the feet.
5. The use of a synthetic fiber liner sock, establishing a double-layer sock system, has been demonstrated to reduce the incidence of blisters compared to single-layer sock systems
6. Socks play an important role in the propagation of fungal infections of the feet.
7. Over the calf socks with elastic compression have not demonstrated benefit for athletes in terms of performance or recovery from training or competition.

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8 Athletic Shoe Lacing in Sports Medicine

Matthew B. Werd

Optimal athletic shoe fit and function depends on a number of factors, including foot type, biomechanical foot function, the type of sport, socks, as well as shoe lacing. Athletic shoelaces and lacing patterns are often overlooked, but can enhance better shoe fit, function, and performance as well as help minimize painful conditions of the foot.

General shoe lacing tips include: loosening the laces before slipping the foot into the shoe, which maintains the integrity of the eyelets and heel counter; tightening the laces from distal (toe end) to proximal (ankle end); and tightening gradually at each set of eyelets. A shoe with more eyelets enables a more custom fit with a variety of lacing patterns.

Athletic Shoelace Materials

Elastic (bungee-like cord) lacing material may be preferred by athletes who want a softer and looser feel and may be beneficial for runners with injuries. The extra flexibility expands and contracts with the foot and may aid healing and reduce pain and discomfort. Shoes with elastic laces may be easy to slip on and off, but they may not provide as much stability and support.

Nonelastic (cotton, braided, or nylon) shoelace material is recommended for athletes with healthy feet who prefer a snug and secure "feel" to their athletic shoes.

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A combination of outer nylon with inner elastic makes a "finger-trap" system, providing both strength and flexibility.

Velcro straps are sometimes used in place of shoelaces, and may be very useful for medical patients who may have a difficult time lacing shoes; however, Velcro straps will not provide as much athletic foot support as tie-lacing.

Newer lacing systems incorporate a steel lace, which can be ratchet-tightened, providing for maximal shoe-to-foot contact and eliminating chance for slippage or becoming untied. More discussion on these lacing systems is included at the end of this chapter.

Athletic Shoelace Shapes

Shapes of athletic shoelaces can also vary, which may affect the ease of tying and tightness of the knot. Different shapes of laces include: traditional flat, thick round "cord-like," oval, and even ribbed for additional knot strength.

Athletic Shoelace Lacing Techniques

Difficult to fit feet and conditions such as narrow heels, high or low arches, or narrow or wide feet can be accommodated by changing the way the shoe is laced. Proper lacing can deliver a secure, comfortable, and supportive fit. Often, a small change to the athletic shoe lacing can make a big difference in comfort and performance.

Figures 8.1, 8.2, 8.3, 8.4, 8.5, 8.6, 8.7, and 8.8 demonstrate a variety of useful lacing techniques, which includes the purpose of the technique, as well as a list of

Fig. 8.1 Standard crisscross lacing pattern. *Technique in detail*: The laces begin at the distal eyelets and are crisscrossed proximally through each eyelet of the shoe. *Purpose*: This is the traditional lacing technique used most commonly in new shoes that come directly "out-of-the-box". *Foot types and conditions for this lacing pattern*: Normal-arched foot, Pathology-free foot

Fig. 8.2 Non-crossing, parallel lacing pattern. *Technique in detail*: Beginning at the distal eyelets, each lace is continued proximally after skipping one eyelet, and is then crossed. Repeat until all eyelets are laced and tied. Notice that with this lacing pattern, the laces do not crisscross each other. *Purpose*: This technique lessens the pressure on the top portion of the arch of the foot, while still securing the foot to the shoe. *Foot types and conditions for this lacing pattern*: High-arched foot, shoes that feel "too tight" on the top of the foot

Fig. 8.3 Outside-eyelet, crisscross lacing pattern. *Technique in detail*: Shoes with eyelets that zigzag up the placket will work best for this technique. The standard crisscross pattern is modified by using only the outside/widest eyelets of the shoe. Tighten from the outer eyelets, pulling the body of the shoe toward the center. *Purpose*: This technique will help to pull up on and support the arch by tightening the shoe to the foot. *Foot types and conditions for this lacing pattern*: Low (flat) arch, posterior tibial tendon dysfunction, narrow foot

foot types and/or conditions which may benefit most by each pattern. Notice that—for demonstration purposes—one-half of the shoelace shown in all figures has been colored black and the other half remains white.

Fig. 8.4 Inside-eyelet, crisscross lacing pattern. *Technique in detail*: Shoes with eyelets that zigzag up the placket will work best for this technique. The standard crisscross pattern is modified by using only the inside/narrowest eyelets of the shoe. Tighten from the inner eyelets, pulling less of the body of the shoe toward the center. *Purpose*: This technique will help to alleviate pressure on the top of the arch by loosening the shoe to the foot. *Foot types and conditions for this lacing pattern*: High arch, dorsal foot ganglion or cyst, dorsal foot exostosis, nerve impingement syndromes (medial dorsal cutaneus nerve or intermediate dorsal cutaneus nerve)

Fig. 8.5 Distal-medial eyelet lacing technique. *Technique in detail*: The picture above shows the left shoe. The black half of the shoelace is threaded through the most distal-medial eyelet (closest to the big toe). Next, it is crossed all the way up through the most proximal-lateral (highest, opposite-side) eyelet to the outside. Leave just enough slack at the top to tie a bow. Take the remaining portion of the lace—the white half of the shoelace shown above—straight across toward the outside of the shoe and then diagonally up toward the inside of the shoe. Repeat until all of the eyelets are laced. *Purpose*: To pull the upper material off of the big toe and decrease the pressure on the great toe and joint. In the above picture, when the black shoelace is tugged and tightened, the distal-medial eyelet (the part of the shoe directly over the big toe) will be pulled away from the great toe and toenail, thereby relieving shoe pressure at this area. *Foot conditions helped most with this lacing pattern*: Black toenail/subungual hematoma of the great toe, subungual exostosis of the great toe Hallux extensus, hallux valgus/bunion deformity, hallux limitus/rigidus, turf toe

Fig. 8.6 "Heel lock" lacing modification. *Technique in detail*: Lace as normal until one eyelet remains proximally on each side. Draw the lace straight up on the outside of the shoe and bring it through the last eyelet, creating a loop, and repeat on the other side. Cross each lace over the tongue, thread it through the opposite loop, and tie. The loops help to cinch in the material around the ankle, which "locks" the shoe to the heel and prevents the heel from slipping without making the rest of the shoe any tighter. *Purpose*: To create a more secure fit around the ankle without tightening the entire shoe. It should be noted that this technique effectively "locks" the heel into the shoe. This common technique provides a much more stable fit, and can easily be combined or added with other lacing patterns. *Foot conditions helped most with this lacing modification*: Narrow heels, heel slippage, heel bullae/blisters, athletes who wear orthoses and have problems with the orthosis moving inside the shoe

Fig. 8.7 Open distal eyelet lacing technique. *Technique in detail*: Skip the most distal set of eyelets (closest toward the toes). Begin lacing at the next set of proximal eyelets (or begin at the second proximal set of eyelets if needed) and continue to lace proximally as usual. **Alternative technique*: *Remove the laces and measure them. Buy two sets (four laces) half of the measured length. On both shoes, use one lace for the bottom three eyelets and a second lace for the upper eyelets. The end result will be two bows on each shoe, allowing the bottom laces to be tied looser (or tied tighter, for a narrow forefoot) to accommodate a wider forefoot. Purpose*: This technique allows more flexibility of the shoe and it loosens the upper of the shoe at the metatarsal-phalangeal joints. *Foot types and conditions for this lacing pattern*: Extra-wide forefoot (or extra narrow forefoot, as noted above), hallux valgus (bunion), Tailor's bunion, Morton's neuroma, hammer toe syndrome, "cramped toes," toenail pathology, Achilles tendon pathology, posterior heel pathology

Fig. 8.8 Open eyelet lacing technique. *Technique in detail*: Draw with a marker or place a lipstick smear on the painful area, or "hot spot" on the dorsum of the foot. Insert the bare foot into the shoe, press the tongue of the shoe against the dorsum of the foot, then remove the shoe. The mark on the underside of the tongue will give an indication as to which set(s) of eyelets to skip. Lace the shoe until reaching the eyelet before the spot, and take the lace back under and pull it up through the next eyelet on the same side. Next, take the lace across and continue to lace, then repeat this on the other side. There will be an empty spot on the tongue where no laces cross it, which should eliminate the pressure point. *Purpose*: To eliminate pressure from a "hot spot" on the top of the foot by lacing around it, and not directly over it. Pressure from tight shoes and/or laces is alleviated at the site of impingement. *Foot types and conditions for this lacing pattern*: High arch, "Hot spot" in which the shoe rubs on one spot on the top of the foot, extensor tenosynovitis, dorsal foot ganglion or cyst, dorsal foot exostosis, nerve impingement syndromes (medial dorsal cutaneus nerve or intermediate dorsal cutaneus nerve)

Athletic Shoelace Technology

Shoe lacing technologies may be helpful to improve fit and performance in specific sports.

Many unforeseen problems can occur during a sporting event, including athletic shoes that come untied. Untied shoelaces can be both a frustrating and dangerous problem, and has prompted the development of advanced lacing systems and lacing materials.

Shoelace-locking systems can keep shoelaces tied and can also affect the ability to quickly slip a shoe on or off the foot. Quick shoe application and secure shoelace locking can be important in sports such as triathlon and adventure races, in which a quick transition time (*T*2) from the bike to the run can be critical. Several common shoelace systems and materials geared to assist improved shoe-fitting through lacing are presented.

Athletic Shoelace Specialized Systems

Athletic shoelaces becoming untied during training or competition can be dangerous as well as harmful to performance. In the past, athletes who have had problems with shoelaces untimely becoming untied during training or competition found it helpful to cinch the shoelaces in a double or triple knot, however, these tend to loosen and need to be retied. Another technique used to prevent athletic shoes from becoming untied includes wrapping athletic tape around the outside of the shoes and laces.

Newer patented lace-locking systems such as "Lock Laces™," "Speed Laces™," and "Yankz!™" use specialty shoelace "locking" designs and materials to help prevent loosening and to improve performance and comfort. Once these lacing systems are fit to the shoe, they need minimal readjusting, and they eliminate floppy, loopy laces. However, one potential concern with these lacing systems remains slippage at the lace/lock interface.

Lock Laces™ are a patented elastic lacing system that feature specially designed elastic laces combined with a spring-activated locking device.

The lace uses curved tips to allow the lace to pass more easily through the eyelet configurations in athletic shoes. The laces are made with water-resistant banded, multi-strands of elastic/bungee.

The lock is a slideable spring-activated device made from a strong, durable, and lightweight plastic which hold the laces in place. The tension springs are made from a metal alloy, resistant to rust and corrosion.

Lock Laces™ use a traditional lacing scheme with specialized laces and a locking mechanism in place of a traditional knot.

Speed Laces™ replace ordinary laces and provide added support and stability, instant tension adjustment, and eliminate the need to retie laces again. Speed Laces™ is a totally secure, closed-loop system in which lace tension is always equal throughout the shoe. Less friction is created at the lace-eyelet interface by using a patented fitting which uses the shoe's existing eyelets.

Xtenex Accufit Compression Laces™ (IndeXed-TENsioning NEXus) is another athletic lacing system that uses an elastic shoelace with expandable knots incorporated into the lace. The knots straighten (goes away when pulled tight) allowing the knot to be pulled through the eyelet, but remains secure when not under tension.

Yankz! Sure Lace System™ is another athletic lacing system that uses an elastic shoelace-locking device which tightens the shoe with one pull of the cord.

Yankz! Sure Lace System™ is another athletic lacing system that uses an elastic shoelace-locking device which tightens the shoe with one pull of the cord.

Greeper Laces™ incorporates two ends of a nonelastic laces tied together replacing traditional bow knot. The replacement bow system never comes undone, and can easily be tightened or loosened—"once applied, always tied." These have been popular with endurance athletes such as those competing in long distance triathlons.

Boa Closure System™ was founded by Southern California surfer who experienced firsthand the shortcomings of traditional laces on snowboard boots and hockey skates. Boa closure systems are now being incorporated into multiple sport shoes including: golf, cycling, athletic, outdoor, running, and triathlon.

Boa closure system comprises steel lace, nylon guides, and a mechanical reel designed to improve upon the performance—fit is "dialed-in" with the simple turn of a knob, free of the stretch, weight, and potential issues of traditional lace closures. Boa systems offer improved durability, light weight, fast and convenient operation, and on-the-fly adjustments.

Solomon Quick Laces™ enables fast easy adjustment of the laces, ensuring that laces remain tied and eliminate loose ends.

Off-road trail events requiring the most secure fit of the foot inside the shoe without any additional movement may benefit most from shoelace-locking systems such as the Boa and Solomon.

Athletic Shoelace Lengths

The length of shoelaces can vary for different shoe types. Table 8.1 is intended to be a "guideline only" for standard shoes. If replacing laces, measure the old laces as a reference.

Summary

Athletic shoelaces and lacing patterns are often overlooked, but can enhance better shoe fit as well as help minimize painful conditions of the foot. Difficult to fit feet and certain foot conditions can be accommodated by simply changing the way the shoe is laced. Proper lacing can deliver a secure, comfortable, and supportive fit, and often, a small change to the athletic shoe lacing can make a big difference in comfort and athletic performance.

Table 8.1 Recommended shoelace lengths based on pairs of eyelets

Hole pairs	Shoelace length
3 or 4	27
5 or 6	36
6 or 7	40
7	45
8	54
9	63
10–11	72

Prefabricated Insoles and Modifications

9

David M. Davidson

Over-the-counter, ready-made, or prefabricated insoles are marketed widely for relief of foot pain. Shoe stores, sporting goods stores, grocery stores, and drug stores have shelves filled with such inserts in all different shapes and sizes. One is able to type "shoe insert" or "over-the-counter foot insert" into a search engine and find more than one million choices. It is not uncommon for the average athlete to self-treat a foot problem using these products prior to seeking professional advice. It is also common for the medical professional to suggest prefabricated insoles before referring them to a podiatric physician or other specialist for care. There are instances when these insoles resolve, or at least improve, the patient's main complaint; however, there are also times when the nonprescription device does more harm than good. Unfortunately, some professionals and nonprofessionals (shoe stores, internet sites, etc.) market over-the-counter insoles as true, corrective orthoses.

The American College of Foot and Ankle Orthopedic Medicine in their practice guidelines published definitions that are now widely accepted. An "orthosis" is a device utilized to assist, resist, facilitate, stabilize, or improve range of motion and functional capacity. A "foot orthosis" is defined as a custom or stock orthosis utilized to treat the foot. A "custom foot orthosis" is a device derived from a three-dimensional representation of the patient's foot. "Prescription custom foot orthosis" is created specifically to address the pathomechanical features of a foot condition that may be structural or functional in nature.[1]

[1] ACFAOM Practice Guidelines, 2005.

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The dictionary definition of "orthosis" is a device "serving to protect or to restore or improve function…".[2] A second, accepted definition is: "an orthopedic appliance designed to straighten or support a body part".[3] If one utilizes these definitions, a custom shoe insert made from a cast in neutral position, or a ready-made device, will satisfy the description of "orthosis." Therefore, it important for the professional to define terms using specific language to inform the patient exactly what he or she is receiving as treatment for their condition.

In order for a shoe insert to be classified as a true orthosis (i.e., prescription custom foot orthosis), the insert needs to be made from a mold of the foot while the subtalar joint is in the neutral position (neither pronated nor supinated). Once the cast is made, the laboratory will construct a device that, while being worn in the shoe, maintains the subtalar and midtarsal joints in the corrected position during active gait, thereby creating a more biomechanically efficient gait. It should be obvious that a store-bought shoe insert, or an insert taken off the shelf chosen strictly by size of the individual's shoe, does not conform to the above description. It has been the experience of this author that retail stores, shoe stores, and some doctor's offices call these store-bought insoles "orthotics" when, in fact, they are not. Common sense should make it clear that simply placing the foot in a foam block and choosing a device based on the configuration of that impression will not satisfy the above definitions. Certainly, pulling a stock shoe insert off the shelf also does not satisfy this designation. Unfortunately, there is no regulation to that prevents retail stores from advertising these inserts as orthoses and charging custom orthotic prices for them.

Dr. Richard Schuster, one of the fathers of lower extremity biomechanics, once said that there is a certain segment of the population that would have fewer symptoms if they were to take a sock and roll it up and place it under the arch in their shoe.[4] These individuals are usually people with rigid, high-arched feet, which does not allow for shock absorption. This is the reason that many people report feeling better with a simple, store-bought insole (Fig. 9.1).

In practice, prefabricated insoles do have significant value in certain circumstances. For example, many people have a limb length discrepancy, either structural or functional. The body at times compensates for this inequality, but there are times when symptoms develop because of this difference. A leg length difference of ½ in. or greater often leads to low back pain, hip pain, and, many times, creates pronation of the longer leg creating foot and ankle issues such as posterior tibial tendonitis and plantar fasciitis. Adding a heel lift onto an over-the-counter shoe insert to compensate for the limb length discrepancy will certainly be helpful.

The athlete with an atrophic fat pad and complains of pain under the metatarsal heads and/or under the heel may benefit from a prefabricated insole with additional cushioning.[5] Several years ago, it was believed that injection of collagen would

[2] Dorland's Medical Dictionary, 2007.

[3] Stedmen's Medical Dictionary, 2004.

[4] Personal Communication.

[5] Hakan Özdemır, M.D., Yetkın Söyüncü, M.D., Mete Özgörgen, M.D. and Kürşat Dabak, M.D., J Am Podiatric Med Association, 94(1): 47–52, 2004.

Fig. 9.1 Store-bought insole

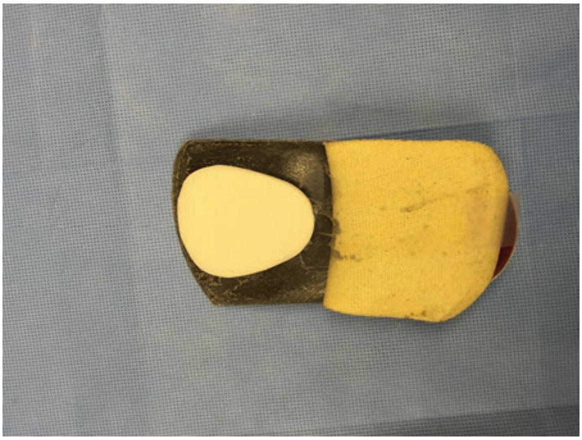

Fig. 9.2 Modifications can be placed on top of or underneath an insert. (From Hakan Özdemır, M.D., Yetkın Söyüncü, M.D., Mete Özgörgen, M.D. and Kürşat Dabak, M.D., J Am Podiatric Med Association, 94(1): 47–52, 2004, with permission of the American Podiatric Medical Association)

benefit such a patient, using it to replace the natural fat cushion lost in the aging process. This procedure proved both costly and ineffectual as it was often displaced and/or lost after a few weeks of weight-bearing. One of the best methods of resolving this complaint is simply cushioning the foot with a full length, soft or semirigid, over-the-counter device. In addition, athletes who play on unyielding surfaces such as asphalt or concrete may also benefit from such cushioning, especially when they wear thin-soled athletic shoes.

Many forms of arthritis are also characterized by degenerative changes that lead to dorsal subluxation of the toes and plantar prominence of the metatarsal heads. Prefabricated insoles are often beneficial in treatment of these individuals. In addition, modifications can be placed on top of or underneath the insert (Fig. 9.2) to further disperse weight from one particular area.

Diabetic athletes may also benefit from a prefabricated insole. Foot problems commonly seen in diabetic patients include vascular impairment, neuropathy, atrophy of the soft tissues, and deformity. The importance of addressing insensitivity,

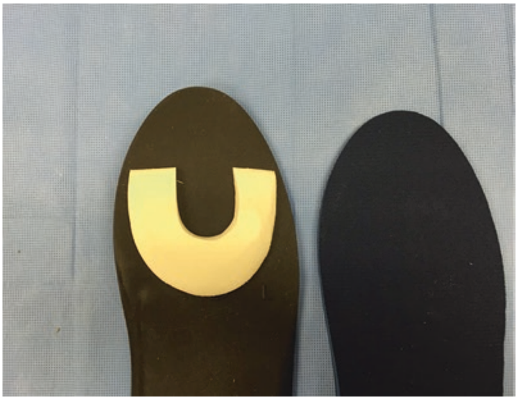

Fig. 9.3 Insoles can also be easily modified with dispersion using a U-shaped pad or metatarsal pad. (From Carine H.M. van Schie, Ph.D., Cristiana Vermigli, M.D., Anne L. Carrington, Ph.D. and Andrew Boulton, F.R.C.P., Muscle Weakness and Foot Deformities in Diabetes, *Diabetes Care* 27:1668–1673, 2004. Copyright © 2007 American Diabetes Association. Reprinted with permission from The American Diabetes Association)

paresthesias, decreased vibratory sense, and motor weakness cannot be stressed enough. Motor neuropathy is commonly believed to lead to weakness in the intrinsic muscles of the foot, upsetting the balance between flexors and extensors of the toes.[6] Atrophy of the small muscles responsible for metatarsophalangeal plantar flexion is thought to lead to the development of hammer toes, claw toes, and prominent metatarsal heads. These deformities are common sites of abnormally high pressure, and repetitive pressure at these sites could result in the buildup of calluses and/or ulceration.

These patients will benefit from prefabricated insoles for the same reason as stated earlier. The insoles can also be easily modified with dispersion using a U-shaped pad or metatarsal pad (Fig. 9.3). These are very helpful in off-loading an area that may be predisposed to ulceration. Diabetic athletes need to be monitored closely and the off-loading material may need to be increased in thickness or placed in other positions if one sees that there is still pressure in a sensitive area.

The same type of off-loading a prefabricated insole may be of benefit in athletes who present with forefoot pain due to other pathology such as neuroma or nerve compression, lesser metatarsophalangeal capsulitis and/or metatarsalgia.

In athletes, whether professional, college, high school, or recreational, prefabricated insoles often have a place in treatment. It is well documented that the forces on the foot are at least three times normal when comparing a running gait to a

[6] Carine H.M. van Schie, Ph.D., Cristiana Vermigli, M.D., Anne L. Carrington, Ph.D. and Andrew Boulton, F.R.C.P., Muscle Weakness and Foot Deformities in Diabetes, *Diabetes Care* 27:1668–1673, 2004.

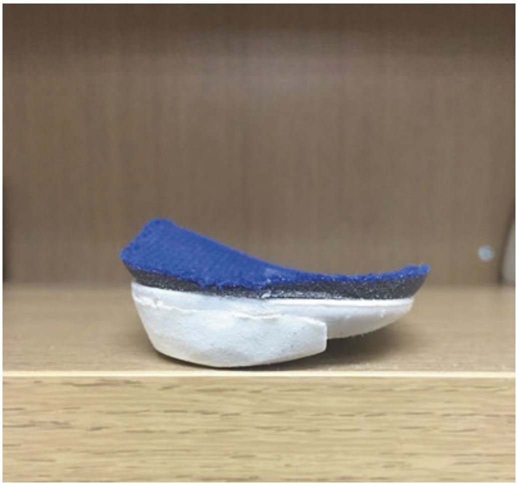

Fig. 9.4 A prefabricated insole may be used as a trial, either alone or with a modification such as a varus wedge

walking gait.[7] These forces may increase when running downhill or on uneven surfaces, predisposing an athlete to an overuse injury. If an individual's biomechanical examination reveals only a minimal discrepancy, then symptoms may not occur in a walking gait, but may become obvious during running. A prefabricated insole may be used as a trial, either alone or with a modification such as a varus wedge (Fig. 9.4), and may be sufficient to eliminate the athlete's symptoms.

Many times the human body will compensate for imbalances, whether they are structural or biomechanical. Care must be taken not to change an individual's biomechanics solely because an abnormality is documented on examination. It is important to address an athlete's flexibility deficiencies before addressing any biomechanical issues noted on examination. Any shoe insert, whether custom made or not, will not work, for example, if the athlete has a gastrocnemius/soleus equinus as there will be premature heel lift off and will have no effect on the motions of the subtalar or midtarsal joint. When treating with an elite athlete, it is especially dangerous to change the biomechanics unless other attempts at treatment have failed. A professional football running back with early posterior tibial tendonitis, for example, has reached this highest level of achievement with certain biomechanics. Why would one consider changing that with such an individual? One would think this person could be treated without modifying his gait.

It is important for an individual to have an understanding of exactly what he/she receives when a shoe insert is purchased. As stated above, people use different terms to describe each product. Many people use the word "orthotics" to describe what professionals call a prefabricated insole. The internet, shoe stores and even some professionals dispense off-the-shelf inserts and will tell the customer they are receiving a device that will solve all their ills. Wearing such a device, especially in

[7] The Lower Extremity and Spine In Sports Medicine, Nicholas Hershman, St. Louis, The C.V. Mosby Company, Vol. 1, Chap. 11, p. 396, 1986.

young children may do more harm than good. It is widely known, for example, that during gait, there is internal rotation of the knee.

Adding an over-the-counter insert in the shoe will change that rotation and may even create rotation in the other direction creating acute symptoms such as lateral knee pain, hip pain and/or low back pain. In addition, placing a device into a shoe not only fills the arch, which at times is good, it may supinate the foot too much causing an excessive amount of stress laterally and may, in fact, create a stress reaction (or stress fracture) in the fourth or fifth metatarsal.

It should be noted that most prefabricated insole are made of a soft or semirigid material. Overweight athletes will, therefore, compress the insole to such an extent that it will limit its effectiveness.

There is a use for prefabricated insoles in the treatment of foot, ankle, lower leg, knee, and low back problems. The professional needs to know when it would be more appropriate to prescribe a custom foot orthosis. It is critical that the athlete makes an educated decision when he or she purchases a prefabricated insole.

Orthodigital Devices in Sports Medicine 10

Matthew B. Werd

Athletes who wear tight-fitting, limited volume shoe gear (soccer/football/baseball/cycling cleats, ballet/dance/aerobic shoes, skating/skiing boots, etc.) and also have digital deformities may benefit from an orthodigital device. An orthodigital device is a custom-made orthopedic appliance used to treat conditions of the digits which have been used successfully for decades [1–3]. These devices can be extremely useful for difficult-to-treat digital conditions in the athlete, which may not respond to traditional care using proper shoe gear and orthoses alone.

Orthodigital devices can be used to relieve pressure, immobilize, and reposition the digits (Table 10.1). These devices can be used in place of athletic taping and padding for conditions which may require prolonged splinting.

An orthodigital device is made from a moldable silicone compound which allows the quick fabrication of interdigital wedges, separators, dorsal toe protectors, and orthodigital splints. These devices can be mixed, shaped, and set in less than 5 min, and they are washable, nontoxic, nonirritating to skin.

The material is smooth, soft, and easily kneadable, which—after adding the catalyst hardening paste/curing agent—achieves a putty-like consistency. After 4–5 min, the device will harden into its permanent form and can then be applied to the athlete's foot, and simple modifications can be made by cutting or grinding.

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Table 10.1 Indications for orthodigital device in the athlete

Digital deformities requiring immobilization or protection
Heloma durum (hard corns)
Heloma molle (soft corns interdigitally)
Fractures of the digits
Hammer toes
Tight-fitting shoes with limited internal volume (such as soccer/football/baseball/cycling cleats, ballet/dance/aerobic shoes, and skating/skiing boots)

Fig. 10.1 Materials needed to fabricate an orthodigital device: silicon compound; hardening/curing agent; scoop measuring device (1 TSP)

Orthodigital devices provide a customizable fit and allow portability (they can be made in an office-setting, in the athletic training room, or even on the sideline). Orthodigital devices provide superior durability versus athletic taping, and they are reusable, washable, and can be removed and reapplied.

Guidelines for Fabrication of an Orthodigital Device

Materials needed (Fig. 10.1)

1. Silicon compound
2. Hardening/curing agent (catalyst)
3. Scoop measuring device (1 TSP)
4. Ruler

Step-by-step process for fabricating an orthodigital device (Figs. 10.2, 10.3, 10.4, 10.5, and 10.6)

Step 1. Obtain the approximate volume of material. Prior to adding the hardening agent, estimate the amount of material needed by making a premold of the digits to be splinted.

Fig. 10.2 Combine silicon compound with 1 cm of curing agent per one scoop (1 TSP) of compound. For a softer device, add slightly less curing agent. For a more firm device, add slightly more curing agent

Fig. 10.3 Mix the compound and curing agent

Fig. 10.4 Continued mixing of the compound and curing agent in hand approximately 20 s

Fig. 10.5 Roll the mixture into a ball

Fig. 10.6 Finally, roll the mixture into an elongated roll before shaping to the athlete's digits, which will help avoid seams in the final shape of the device

Step 2. Mix the correct amount of hardening agent with the material. Check the package instructions for the proper ratio of hardening agent to be added to the selected volume. The usual ratio is 1 cm of curing agent per 1 TSP of compound.

Step 3. Mold the mixture to the digits into the correct position. Apply Saran wrap or a plastic bag to the foot to protect the orthodigital device, and then place the athlete's foot into the appropriate athletic cleat/shoe/boot. Allow weight-bearing while the orthodigital device is hardening.

Step 4. Confirm the fit and function of the orthodigital device with the athlete. If the position or hardness of the orthodigital device is not satisfactory, then repeat the process again until correct.

A clinical example of a common clinical application of an orthodigital device used for an athlete is shown in Figs. 10.7, 10.8, and 10.9.

Fig. 10.7 Clinical example of orthodigital device used to support and immobilize a fractured second digit in a competitive triathlete. A. Fractured second digit

Fig. 10.8 Orthodigital device shown after molding process

Fig. 10.9 Orthodigital device in place to support the fractured second digit

Summary

Orthodigital devices are custom-made orthopedic appliances which are used to treat multiple conditions of the digits in the athlete. These devices can be extremely useful for difficult-to-treat conditions which may not be amenable to traditional care using taping, padding, shoe gear, and orthoses. Orthodigital devices can be used in place of athletic taping for conditions which may require prolonged splinting. Orthodigital devices provide one more option to the sports medicine practitioner in treating troublesome athletic injuries to the digits.

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Evidence-Based Orthotic Therapy in Sports Medicine

11

Paul R. Scherer

The origins of orthotic therapy in sports medicine began in the early 1970s when authors Jim Fixx, M.D. (The Complete Book of Running) [1] and Harry F. Halvac, D.P.M. (The Foot Book: Advice for Athletes) [2] provided both the public and the medical community anecdotal information about the mechanical origins of foot pathology in athletes and the possible value of custom functional foot orthoses. Most of the American medical community was overwhelmed by the injuries sustained during the latest fitness craze, jogging, and wanted medical solutions to the large numbers of complaints arising from the running rage.

Primary care physicians, podiatrists, and orthopedic surgeons who had rarely seen stress fractures, ruptured Achilles tendons, and plantar fasciitis were now overrun by patients who addicted themselves to recreational jogging and started competing in fun runs or even marathons. The medical literature and continuing education environment provided little help to the medical community and valid information on either prevention or treatment of the resulting injuries and pathology did not exist. A few texts, written for sports trainers, suggested taping and strapping as a broad solution to many injuries but these therapies had wildly diverse techniques, methods, and obviously extremely unreliable outcomes.

Somehow, the podiatric medical profession was able to intellectually connect the mechanical origins of many of the sports and exercise-related injuries to the preventative and therapeutic mechanical benefits of orthoses. With the recommendations of the previously mentioned texts they began an informal national experiment of orthotic therapy on their patients. This adventure and the resulting positive anecdotal evidence created an interest that created sports medicine professional associations, orthotic laboratories, special foot products related to sports, and a huge

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number of continuing educational opportunities for medical professionals to learn about prescribing and constructing orthoses.

This era was followed by publications, existing and new, supported by professional organizations, dedicated to sports medicine and including some original but not necessarily scientific information related to the effectiveness of functional and soft orthoses. Since the emerging sport shoe industry viewed the origins of pathology, at the time, to impact forces, the original investigation focused on impact reducing orthotic devices rather than functional devices that would change or alter the motion of the foot [3, 4].

Slowly the professions and sports medicine community recognized that there will be a continued interest in regular physical activity, that injuries are a common problem in physical activity of healthy individuals; that most pathology is the result of overuse, training errors, and poor foot wear; and finally that many of these problems can be ameliorated or even prevented by custom functional orthoses, especially in the runner with excessively pronated feet [5].

These realizations, in turn, lead to the investigation, with orthotic therapy of individual mechanically induced pathologies and eventually to pathology-specific orthoses for the control, treatment, or prevention of the symptoms related to these pathologies.

This chapter will investigate the evidence in the literature of the effectiveness of orthotic therapy in certain pathologies. It is well understood that the pathologies discussed are limited in the context of the total knowledge of the subject. Also, it is understood that the evidence is limited to the available state-of-the-art technology, evolving sport shoe construction, and the variety of both sport surfaces and the individual's unique foot and ankle mechanics. There will be more evidence in the near future.

The first significant evidence on the effectiveness of foot orthoses on specific sports medicine pathology was a retrospective cross-sectional survey published in the American Journal of Sports Medicine in 1991 [6]. The study, done at a moment in time where there was an estimated 30 million recreational runners in the United States, estimated that 60% of sports participants would experience an injury [7, 8].

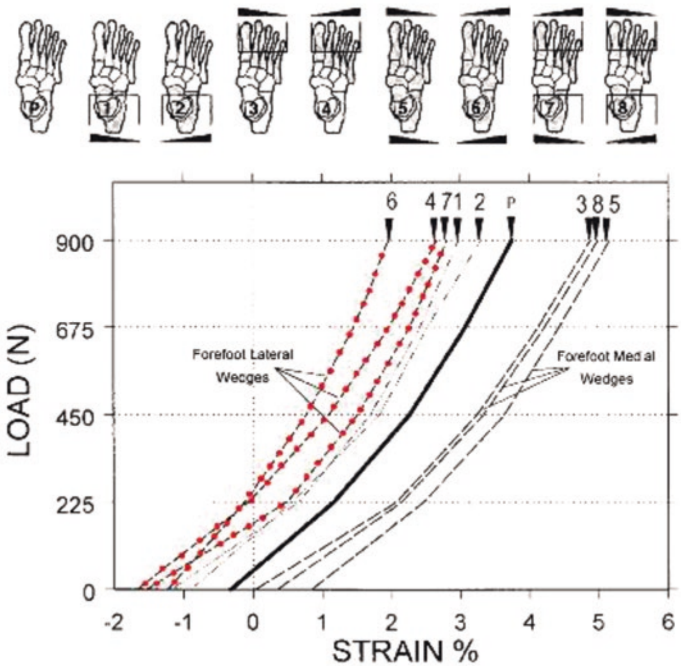
Five hundred questionnaires were distributed to runners who were using custom orthoses for the symptomatic relief of lower extremity complaints including plantar fasciitis, patellofemoral disorders, and a variety of tendinitis. 75.5% of the respondents reported complete resolution or great improvement of their symptoms. Ninety percent of the respondents demonstrated a significant satisfaction with orthotic therapy because they continued to use their orthoses even after resolution of their symptoms.

Since the publication of this survey, there has been much more specific evidence on the effect of custom functional orthoses on specific pathologies. The remainder of this chapter will investigate the evidence on plantar fasciitis, functional hallux limitus, patellofemoral and medial knee pain syndrome, and tarsal tunnel syndrome. Following chapters will provide recommendations based on the literature evidence, on specific prescriptions to meet the pathomechanical uniqueness of each entity, as well as several others.

Plantar Fasciitis

Plantar fasciitis is the common vernacular for mechanically induced subcalcaneal pain, presenting as first step pain and tenderness at the medial tubercle of the calcaneal tuberosity as a result of abnormal foot mechanics [9]. The plantar fascia is part of a windless mechanism, which creates tension with dorsiflexion of the great toe, a component of most sports [10]. Today it could be the most common and persistent problem affecting the foot of athletes, regardless of sport. Foot orthoses are an accepted mechanical treatment for this pathology; however, the numerous variations in foot orthoses make it difficult to determine which variable is responsible for the change. One study showed that mechanical treatment with only custom orthoses designed to prevent midtarsal joint collapse during gait resulted in 89% of subjects getting relief from their symptoms [11].

Many practitioners believe that pronation of the subtalar joint is the primary mechanical instigator of this pathology, but Kogler demonstrated that pronation alone does not produce greater tension on the plantar fascia, but rather the tension originates from any foot type or change in plantar surface that supinates the midtarsal joint (inversion of the forefoot to the rear foot) [12]. Kogler also demonstrated that a wedge under the lateral aspect of the forefoot significantly reduced the strain on the plantar aponeurosis and suggested that this may be effective for the treatment of plantar fasciitis. (Chart A) Many practitioners also believe that plantar fasciitis is an inflammatory process but actually histologically there is fibrosis and thickening of the fascia with collagen necrosis, chondroid metaplasia, and subperiosteral osteogenesis which all suggests a repair process secondary to micro tears from repetitive strain [13]. The following outcome studies provide additional evidence to support treatment with custom and prefabricated orthoses for plantar fasciitis.



The first study by Pfeffer [14] was a well-publicized study that compared the effectiveness of stretching alone to stretching in combination with one of four different shoe inserts in the treatment of plantar fasciitis. Shoe inserts included three prefabricated pads (silicone heel pad, ¾-length felt pad, rubber heel cup), and custom foot orthoses. Though the conclusion states that prefabs along with stretching "is more effective than custom orthoses," an analysis of the statistics shows that all five treatment groups had an improvement in both pain scales, with no significant difference among the groups in the reduction of overall pain scores after 8 weeks of treatment when controlled for covariates. This misleading conclusion prompted a deeper look into the study details to determine why the authors would have made a statement that was not supported by their data.

A retrospective analysis of this work shows that the device type was not consistent. Forty-five percent of the custom orthoses were rigid polypropylene (normal width, 14–16 mm heel cup, no posts or top covers). Another 38% were identical except that the flexibility was semirigid. The flexibility variance was not evaluated in this study, nor mentioned as a variable that could affect outcomes. The remainder of the orthoses (17%) varied dramatically. Variables other than shell flexibility that were altered included heel cup depth (range 8–18 mm), width (narrow–wide), use of a rearfoot post, and use of a top cover. The authors noted that patients were encouraged not to change their regular shoe wear. Did the authors believe that a narrow device with a 8 mm heel cup was equivalent to a wide device with a 18 mm heel cup for a patient with plantar fasciitis, or were they accommodating the patient's shoe choice as limited by their protocol? Improper footwear has been identified as a contributing factor in plantar fasciitis [15].

Another variable with the orthoses in this study involves the negative cast. Custom orthosis studies generally allow only a single experienced practitioner to cast each patient, minimizing any effect of the casting process on orthosis outcomes. It appears that 13 different practitioners casted the 42 subjects, with these practitioners learning to cast by watching a video. Considering the number of uncontrolled variables in the custom orthoses group, it is unclear how the authors drew any conclusions about the efficacy of custom orthoses in the treatment of plantar fasciitis, or justified a comparison to the other treatment groups. Fortunately, there have been other outcome studies in the treatment of plantar fasciitis.

Another positive evaluation of custom orthotic therapy for plantar fasciitis by Lynch [16] evaluated the effect of three widely accepted treatments: anti-inflammatory (injected and oral NSAIDs), accommodative (viscose heel cup and acetaminophen), and mechanical (low-Dye strapping followed by custom foot orthoses). This randomized prospective study found that 70% of the patients in the mechanical therapy group had improvements in pain and function, significantly better than the accommodative (30%) or the anti-inflammatory (33%) groups. Only 4% of the mechanical group had treatment failure, as opposed to 42% for the accommodative group and 23% for the anti-inflammatory group. The authors concluded that mechanical control with custom orthoses is more effective than anti-inflammatory therapy or accommodative therapy used in this study.

Martin [17] published a prospective randomized study that evaluated the effectiveness of three different mechanical modalities used in the treatment of plantar fasciitis including over-the-counter arch supports, rigid custom-made orthoses with a heel post, and night splints. Though all three devices were effective as initial treatments for plantar fasciitis after 12 weeks of use, "there was a statistically significant difference among the three groups with respect to early patient withdrawal from the study due to continued severe pain, noncompliance, or inability to tolerate the device. Patient compliance was greatest with the use of custom-made orthoses."

Langdorf [18] conducted a randomized trial that evaluated the short-term and long-term effectiveness of foot orthoses in the treatment of plantar fasciitis. The three treatment arms were: sham orthosis made of soft, thin EVA foam molded over unmodified plaster cast, prefabricated foot orthosis made from firm density polyethylene foam, and Root functional custom foot orthosis. Both the prefabricated orthoses and the custom orthoses produced statistically significant improvements in function at 3 months. The authors noted that more participants in the sham group and the prefabricated group broke protocol than in the custom group.

Roos [19] evaluated the effect of custom-fitted foot orthoses and night splints, alone or combined, in treating plantar fasciitis in a prospective randomized trial with 1-year follow-up. The authors concluded that custom foot orthoses and anterior night splints were effective both short-term and long-term in treating pain from plantar fasciitis with all groups improving significantly in all outcomes evaluated across all times. "Parallel improvements in function, foot-related quality of life, and a better compliance suggest that a foot orthosis is the best choice for initial treatment of plantar fasciitis."

A Cochrane database review and a meta-analysis both published in 2008 attempted to evaluate the evidence of orthoses reducing pain in patients with plantar fasciitis [20, 21]. Five trials, which included 691 participants, demonstrated that "although there is limited evidence on which to base clinical decisions regarding the prescription of custom-made foot orthoses…there is silver evidence for painful plantar fasciitis and hallux valgus" [21].

The meta-analysis focused on the randomized controlled trials or prospective cohort designed studies containing self-reported improvement in pain in patients with plantar fasciitis. The conclusion of the report stated "the use of foot orthoses in patients with plantar fasciitis appears to be associated with reduced pain and increased function" [20].

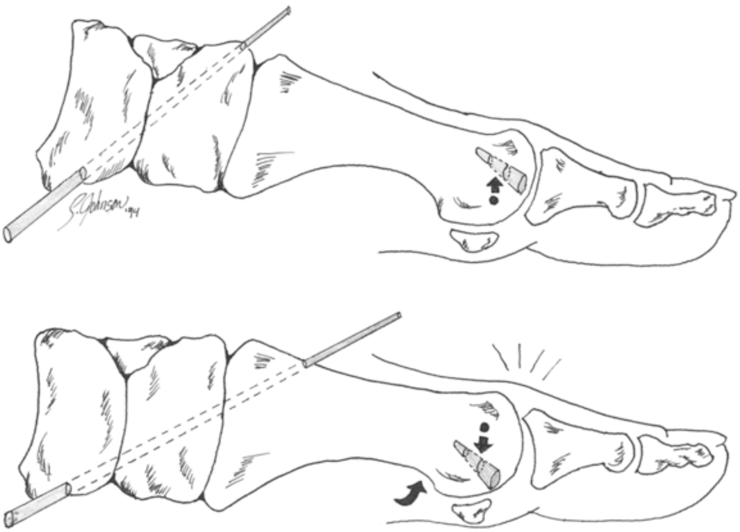
Lastly, a presented but unpublished (or) in press report by Wrobel attempted to associate custom, prefabricated and sham orthoses with reduced pain and improved activity. The study includes 77 participants who were monitored on various measures. Although all groups reported improvement in morning pain, the custom orthotic group had a spontaneous increase in physical activity wearing their orthoses [22].

Although at first glance the data on the efficacy of orthotic therapy for plantar fasciitis in the athlete appears conflicting, every study supports the use of custom orthoses. Each study leaves little doubt that this pathology is mechanical in origin and effective treatment is accomplished through mechanical control by custom orthoses.

Future research may shed light on which modifications of custom orthoses may be most effective in controlling the midtarsal joint motion to prevent stretching of the plantar fascia.

Functional Hallux Limitus

Forcing any joint to move beyond its natural or restrictive range of motion produces forces that cannot be dissipated and results in deterioration, deformity, and pathology. One of the most affected joints in the lower extremity to this situation is the first metatarsal phalangeal joint. Raising the heel in most non-boot sports further than the first metatarsal phalangeal joint is capable of dorsiflexing produces unwanted pressure under the hallux and ultimately motion of this joint on other planes than the sagittal. The inability to dorsiflex the hallux during sports or the forced dorsiflexion in the absence of adequate range of motion produces forces that create pathology including inflammation of the soft tissue under the hallux, deterioration of the cartilage from pressure and subchondral bone as well as proliferation of the osseous structures of the first metatarsal phalangeal joint.



Functional hallux limitus is defined by several authors as 12° or less of restricted hallux dorsiflexion in closed kinetic chain, while there is 50° or greater motion in open kinetic chain examination. Functional hallux limitus is suspected to be the pathology behind the development of hallux abducto-valgus, hallux rigidus, hallux pinch callus, and subhallux ulcerations [23]. This section will review functional hallux limitus (FHL) only, and not structural hallux limitus (SHL), since treatment of the latter, with orthoses, is seldom mentioned in the literature and is suspected to be ineffective.

Whitaker [24] established a definitive relationship between foot position and hallux dorsiflexion. This study used low-Dye strapping for mechanical control and evaluated its effect in 22 subjects. The study demonstrated that the mean range-of-motion before application was 24.7° and 31.81° after application showing statistical significance. This provided quantifiable data demonstrating that changing the foot mechanics similar to that produced by an orthoses can reverse the joint restriction found in hallux limitus.

Grady's [25] retrospective analysis evaluated patients with functional hallux limitus treated with various surgical and nonsurgical modalities [3]. Hallux limitus was defined for this study as less than 10° of hallux dorsiflexion. Forty-seven percent of the patients with symptomatic hallux limitus were successfully treated with custom orthoses alone.

The most recent evidence of the effect of orthoses on functional hallux limitus was published in 2006 [23]. This study evaluated the effect of a Root orthoses (made from a negative cast with the first ray plantarflexed) on hallux dorsiflexion in patients with functional hallux limitus of 12° or less. Forty-eight feet of 27 subjects were tested both in stance and in gait, with and without orthoses. The results demonstrated an increase in hallux dorsiflexion with orthoses in 100% of the subjects, both in stance and in gait. When the orthoses were used in stance, hallux dorsiflexion showed a mean increase of 8.8° or 90% improvement. The gait evaluation methodology used a reduction in subhallux pressure following heel lift as a determinant of increased hallux dorsiflexion. The functional orthoses resulted in a mean reduction in subhallux pressure of 14.8%. This study proved that in all subjects, orthoses reversed to some degree the joint restriction found in hallux limitus.

The mechanical origins of hallux limitus and hallux valgus have been debated for years, including the possibilities of genetic or shoe-related origins. We now have ample proof that the joint restriction is due to abnormal foot position and, most importantly, this limitation can be reversed by custom orthoses as well as the symptoms of hallux limitus and hallux valgus reduced [21].

Tarsal Tunnel Syndrome

Most sports medicine health professionals always suspected a casual relationship between over pronator athletes and symptoms of tarsal tunnel syndrome. Apple [26] was the first to document that this entity was common to long distance runners and the first to recommend a custom orthotic device, especially before intervention with injection therapy or surgical decompression.

Keck [27] first described tarsal tunnel syndrome (TTS) as pain in the proximal medial arch and paresthesia along the lateral and medial plantar nerves. He noted that the foot was often excessively pronated at the subtalar joint in TTS. The etiology was hypothesized to be traction on the tibial nerve and compression of that nerve by the flexor retinaculum or compression of the medial plantar nerve as it perforates the fascia. No clinical outcome studies document orthotic effectiveness for TTS; however, three recent studies on the pathomechanics of TTS indicate why foot orthosis therapy would decrease symptoms.

Trepman [28] measured the tarsal tunnel pressure with the foot in various positions. The positions measured in this cadaveric study were: neutral heel position with mild plantarflexion, everted heel position with mild dorsiflexion, and inverted heel position with mild dorsiflexion. They found increased pressure in the tarsal tunnel when the STJ was pronated, and reduced pressure in the tarsal tunnel when the STJ was supinated and mildly plantarflexed.

Labib [29] evaluated 286 patients with heel pain over a 3-year period. The authors identified 14 patients who were diagnosed with the triad of plantar fasciitis, posterior tibial tendinitis, and tarsal tunnel syndrome (heel pain triad). The authors believe that the triad may be a stage of breakdown of the static arch (plantar fasciitis) and dynamic arch (posterior tibial tendonitis) and may result in a variable degree of arch collapse leading to TTS. They also postulated that the "lack of muscular support of the longitudinal arch produces traction injury to the tibial nerve and results in tarsal tunnel syndrome."

Kinoshita [30] developed a diagnostic test for TTS that sheds light on its etiology and treatment. The foot was passively held in maximal dorsiflexion and eversion for 5–10 s (with all metatarsophalangeal joints maximally dorsiflexed) to create non-weightbearing STJ pronation. Patients diagnosed with TTS were tested preoperatively and postoperatively, with results compared to a control group. No symptoms were induced in the control group with this test. Preoperatively, 97.7% of patients with TTS had an increase in local tenderness, while 95.3% had an increase in Tinel's sign. The study confirms that this test is an excellent diagnostic tool for TTS and provides evidence that holding the foot in a non-everted position with an orthosis may improve symptoms.

This evidence shows, without a doubt, that tarsal tunnel syndrome is of mechanical origin. The activity of the long distance runner makes this pathology frequent and more intractable. The origin starts with eversion of the rear foot and lowering of the longitudinal arch increasing the pressure in the tarsal tunnel. Custom functional orthoses can be designed to reverse this mechanism by increasing the longitudinal arch plantarflexing the ankle as well as preventing rear foot eversion. A pathology-specific device to accomplish this is discussed in the next chapter.

Knee Pain

The dynamics of internal rotation of the leg as a result of subtalar joint pronation and midtarsal joint motion is exaggerated in most sport activities. Since the knee joint has limited transverse plane motion, any motion of the foot that causes greater internal limb motion than the knee can tolerate would logically produce forces that can possibly produce damage and symptoms to the knee joint. The ability of an orthotic device to limit either of these motions can have a dramatic effect on the pathology such as patellofemoral pain syndrome, medial knee pain, and medial knee osteoarthritis symptoms. Most of the kinematic and kinetic data suggests that there is a direct correlation between limiting STJ and MTJ motion and the reduction of symptoms. The exact mechanism of orthoses or the best material, additions, extensions, construction, and cast corrections have been yet delineated.

Saxena [31] was able to define and diagnose in a retrospective review of 102 athletic patients with patellofemoral pain syndrome. All subjects demonstrated an abnormal varus foot deformity. 76.5% of the patients were improved at their first follow-up visit and 2% were asymptomatic by that time. The group with improvement showed a statistically significant decrease in the level of pain related to the use of the orthoses.

Stackhouse [32] performed kinematic and kinetic studies to delineate the amount of internal rotation and adduction of the knee in athletes both with and without functional orthoses. The authors sought to identify a difference in the rearfoot strike patterns of the 15 subjects and relate the variance to foot orthoses. One segment of their analysis showed that orthosis intervention did not change the rearfoot motion but did change the internal rotation and abduction.

Rubin [33] investigated the effects functional orthoses with a lateral valgus wedge might have in patients who had significant medial knee pain and associated disability and osteoarthritis of the knee. Tirty subjects were confirmed to have osteoarthritis of the knee radiographically in the medial compartment. Each patient was casted for and dispensed a custom orthoses with a 5° lateral valgus heel wedge. The visual analog scale at dispensing, 3 weeks and again at 6 weeks, showed a significant reduction in pain. The reduction in pain was greater in individuals with less severe osteoarthritis, possibly suggesting that early intervention is an optimum treatment strategy. All of the subjects reported some reduction of symptoms at the 6-week threshold confirming the casual relationship of orthoses.

Patient outcome studies and kinetic studies confirm that custom functional orthoses may have a more proximal effect on symptoms and pathomechanics than just isolated to the foot and ankle. This is confirmation that the investigation of the effect of custom orthoses is far from complete especially in the athlete. Investigation has now begun to appear in the literature that demonstrates that these devices, if made correctly, may also have a positive effect beyond the knee, including the hip and back.

Jim Fixx and Harry Hlavac, four decades ago, saw a paradigm in sports medicine that has been realized today. Orthoses and orthotic therapy has now reached a level of scientific validity in many respects related to many pathologies. Also, orthoses have offered not only a proven treatment for some of the problems but have also reached a level of preventative medicine. Further investigation into pathology-specific and sports-specific orthoses may show an even greater efficacy and possibly performance enhancement.

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Custom Foot Orthoses Prescription for the Athlete

12

Paul R. Scherer

A well thought out prescription for custom foot orthoses (CFO) that takes into consideration the dysfunction of that particular athlete's foot and the activity of the athlete is a prerequisite to a successful clinical outcome. Addressing the specific needs of the pathology producing the dysfunction as well as the symptoms the athlete is experiencing makes the difference between treatment success or failure and patient satisfaction or frustration. Dispensing the same orthosis for posterior tibial dysfunction and plantar fasciitis will not produce the same successful outcomes for both because these are different pathologies with different functional needs and different mechanical origins.

Clinicians should stop thinking generic custom orthoses and embrace the concept of pathology-specific orthoses. Selecting custom orthoses with disregard for the particular pathology or foot type of an athlete is as effective as selecting an antibiotic without regard to the pathogen or the physiologic condition of a patient. Although there is adequate information in the literature about what type and modification of orthoses are best used for specific pathologies, little information exists about what type and modification are best utilized for a specific sport.

A systematic approach to constructing the most effective orthoses for a patient's specific pathology takes only a little more time and effort than making generic orthoses. The following considerations help to select the various components for an orthoses. The steps include embracing the concept of pathology-specific orthoses, and then prescribing correct material flexibility, positive cast modifications, posting, intrinsic accommodations, and special additions.

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A review of the literature has shown that altering the position of the foot may contribute to improved function of some feet. Published research has described how an orthosis that is designed to invert the calcaneus can significantly reduce the pressure on the posterior tibial nerve in the tarsal tunnel syndrome [1]. Placing a greater valgus correction on the forefoot portion of the orthoses dramatically reduces pull or strain on the plantar fascia as compared to varus correction on the rearfoot [2]. Repositioning the first ray both by casting method and by certain forefoot extensions can improve the range of hallux dorsiflexion in functional hallux limitus [3].

Knowing about the new concepts and still prescribing the same custom orthoses, regardless of pathology, is not providing patients with quality care that produces an optimum clinical outcome. Understanding what foot dysfunction caused the symptoms and focusing on a device design that works to reverse the dysfunction is the goal of pathology-specific orthotic therapy.

Material and Flexibility

Select material and flexibility for the body of the device that meets the needs of the patient's foot type and pathology. The two most common materials used in the United States and Canada are polypropylene and graphite composite. The comparative value of these materials is not as important as the concept that each material has several thicknesses or flexibility and each flexibility is specific to the needs of different foot types, pathology, and occasionally to the sport activity of the patient.

One prospective non-randomized study did compare a thermoset material to the traditional polypropylene used to treat professional athletes. Subjects were able to perceive a significant difference of orthosis weight, resilience, and springiness. The subjects preferred the overall comfort of the thinner thermoset material [4]. The study did not determine a greater effectiveness related to the pathology, but assumptions can be made between comfort and patient compliance.

This chapter cannot provide the appropriate flexibility for every foot type and pathology, but a few examples will give the concept and the direction for improved outcomes. The ultimate combination of factors must be determined by the clinician for each individual athlete. The thinner the polypropylene, the more flexible the device will be, depending on the weight of the patient. There is a difference between milled and vacuumed polypropylene. A milled polypropylene device, since it was never heated for molding, is inherently more rigid at a particular patient weight. Conversely, the polypropylene in a vacuum-formed device has been essentially melted and develops a more flexible characteristic. Orthotic laboratories that use polypropylene will either ask for the desired flexibility, on the prescription form, or ask for the desired thickness. Orthotic laboratories that use graphite alter the formulation to make the devices more flexible or rigid for a particular patient weight.

The following two examples show how flexibility relates to foot types and pathology. Pathology related to gastroc-soleus equinus is difficult to control because the source of the deformity is such a powerful pronator and midtarsal joint deformer. Many clinicians use rigid devices for powerful pronators for better control but actually this places the foot between the proverbial rock and a hard place, producing greater symptoms from the rigid orthoses than from the pathology. Compromising the rigidity of the device in this particular situation, by making it more flexible, maintains some but not total control of the deformity and allows the device to be tolerated. A runner with limitation of ankle joint dorsiflexion and compensation at the midtarsal joint needs a less rigid device. The opposite of this situation is controlling the extremely pronated foot with tarsal coalition or the peroneal spastic flat foot or adult acquired flat foot from PT dysfunction. Nothing but a rigid device will control this pathology and the more the patient weighs, the thicker the polypropylene must be to produce a rigid device.

Polypropylene Shell Rigidy Guidelines*

Vacuum-Formed

	<100 lb	100-150 lb	151-200 lb	201-250 lb	>250 lb
3mm	Semirigid	Flexible	Very Flexible		
4mm	Rigid	Semirigid	Flexible	Very Flexible	
5mm	Very Rigid	Rigid	Semirigid	Flexible	Very Flexible
6mm		Very Rigid	Rigid	Semirigid	Flexible

Direct-Milled

	<100 lb	100-175 lb	176-250 lb	251-325 lb	>325 lb
2mm	Semirigid	Flexible			
3mm	Rigid	Semirigid	Flexible	Very Flexible	
4mm	Very Rigid	Rigid	Semirigid	Flexible	Very Flexible
5mm		Very Rigid	Rigid	Semirigid	Flexible
6mm			Very Rigid	Rigid	Semirigid

*The above rigidity charts are guidelines only. Shell flexibility can vary with foot shape, foot size, prescription options and manufacturing techniques.

Correction and Positive Balancing

Another important parameter of the orthosis prescription is orthosis shape and positive cast work. Cast correction is the term used to "balance the positive cast to neutralize the compensation motion of forefoot valgus or varus." Once a positive is made, either electronically or in plaster, from the negative impression, it contains the forefoot deformity. In a forefoot varus the positive will appear to have an everted heel when placed on a level surface and the opposite for valgus. The cast correction technique is the creation of a platform at the fore part of the positive cast that makes the heel perpendicular. This new shape of the positive and subsequent orthosis is intended to prevent the consequences of midtarsal joint compensation for the forefoot to rearfoot deformity.

This essential part of orthosis construction has drifted tremendously in the past decade. Some orthotic laboratories have completely or partially discarded the cast correction or balancing technique for either reducing cost or out of ignorance of the purpose of the technique. Eliminating this step produces a foot orthosis that is a similar shape as the pathologic shape of the foot in stance and doing little to prevent the consequential compensation of an abnormal forefoot to rearfoot position. The resulting device, without balancing, is little more than an arch support from the 1950s and probably has the same effect as a drug store prefabricated device. The practitioner is urged to investigate whether a cast correction technique is actually performed by the orthotic laboratory producing their device.

The orthotic prescription must include heel cup depth, orthosis width, cast fill, medial skive, and positive cast inversion. Examples of how each relate to some pathologies can be described but obviously not how they relate to all foot pathology.

Heel cup depth, from most orthotic labs, includes shallow (10 mm) standard (14 mm) deep (18 mm) and extra deep. The primary concept to remember when choosing a heel cup depth is the deeper the heel cup, the greater the surface area of plastic and the greater the control of the rearfoot. If the calcaneus is everted, a deep heel cup will provide greater control. The only reason to use a standard or shallow heel cup in the presence of an everted calcaneus is to accommodate the patient's athletic shoe selection, or because the pathology originates distal to the midtarsal joint. A rigid ski boot or hockey skate is so stable that heel cup depth is of little consequence. An attempt to treat posterior tibial tendinitis with an orthosis with a shallow heel cup is an effort in futility.

Orthosis width generally refers only to the width of the distal edge of the orthoses and the resulting breadth of the arch area. Width determines the stability of the orthotic in the athletic shoe during and after midstance and control over the first ray. The longest horizontal support against frontal plane motion of the orthosis in the shoe is the distal edge. The wider the orthoses, the less likely it will tilt with pronation at midstance. When treating pathology that involves excessive midtarsal joint motion, like plantar fasciitis and functional hallux limitus, a wider front edge withstands the deforming forces that are present in a dysfunctional foot. An orthosis raises the base of the first metatarsal to increase hallux dorsiflexion in functional hallux limitus. If the orthosis is narrow, it cannot create a force to hold the base of the first metatarsal up. A wide front edge is rarely an athletic shoe problem, with the exception of extreme styles like soccer cleats. Insisting on choosing orthosis width appropriate for the patients' pathology rather than allowing the orthotic lab to default to narrow so that the CFO fits in any shoe is essential.

Cast fill was originally introduced by Dr. Merton Root [5] as a technique intended to blend the forefoot correction into the arch of the positive. An orthotic lab should offer several cast fills to address the need of a specific pathology. An orthosis made from a positive cast with minimum fill will conform close to the arch of the foot. Minimum fill offers the most control over arch collapse and is essential for symptoms produced by cavus feet and hard to control pronated feet.

Standard fill lowers the arch slightly and makes the orthosis less "tight" against the foot in stance. This is useful when there are secondary issues with the foot, like limitations of motion secondary to osteoarthritis or intense sport activities both of which require a more gentle control of the foot. Maximum fill for equinus, muscle spasm, or tarsal coalition is a strategy that allows for minimum control in situations where the least control can produce enough symptom reduction without creating other problems. Again, allowing the laboratory to select the arch fill without knowing the condition of the patients' foot could produce a clinical failure or a very uncomfortable orthoses.

It is critical that the practitioners control how much cast fill is added to the positive cast. Adding excessive cast fill is a common lab error practice since it produces a more forgiving CFO with less potential to cause arch irritation. Although somewhat less likely to cause arch irritation, an orthosis made from a positive cast with excessive fill will result in an orthosis with inadequate control, since the corrective forces that an orthotic device creates are ameliorated. Prescribing a minimum fill orthoses can be confirmed by matching it to the arch of the foot closely when the foot is held in casting position before dispensing.

The medial skive technique was probably one of the most significant and effective developments in orthosis design. This contribution to the custom functional Root-type design, developed by Kevin Kirby, D.P.M. [6] allowed for the manipulation of ground reactive force to provide better control of the rearfoot. Treating athletes with flexible flatfoot, plantar fasciitis with an everted heel, or PT dysfunction without this modification usually produces a less than optimal result. Most pathologies that include an everted calcaneus in stance are treated more successfully with this technique, which produces a rise in the medial side of the heel cup by 2, 4, or 6 mm. Clinicians who are introduced to this modification frequently discover significantly improved clinical outcomes when they add this modification to the prescription of patients with pathology related to an everted calcaneus. This modification is not effective with a shallow heel cup; it requires a deep or at least standard depth. Most labs don't charge for this additional modification.

Selecting the most appropriate rearfoot post is very important in the athlete. The original design, during the introduction of orthoses, included this hard plastic foundation for the rear portion of the device. Its purpose was to stabilize the orthosis in the shoe during midstance and not to invert the device nor correct for heel varus or valgus which is a common misconception. There is no other proven benefit or purpose for a varus rearfoot post, and logically it doesn't make any sense to invert the front edge of the orthotic by increasing the rearfoot post varus.

Is a rearfoot post necessary for every pathology? No one knows. A prospective study to treat plantar fasciitis demonstrated a positive outcome in 85% of the patients treated with low dye strapping and followed by functional semirigid orthoses [7]. None of the orthoses in this study had a rearfoot post. If you use a rearfoot post to stabilize the orthoses, a polypropylene post seems to be the most durable. Heel strike in some sports can significantly deform an EVA rearfoot post. Some labs offer a variety of shock-absorbing materials but today's athletic shoes are engineered to serve this purpose more effectively. Some labs offer soft posts but within a few months the plantar surface of a soft post has rounded, losing its stabilization quality. Anecdotal evidence seems to indicate that for most pathology hard plastic rearfoot post stabilizes the orthosis by increasing the plantar surface area, reinforcing the shape of the heel cup and extending the life of an orthosis.

Orthosis Extensions and Additions

Selecting the forefoot extensions and special additions that make the orthosis specific to the needs of the particular pathology and the patient is vital to a positive outcome. Although there are literally hundreds of combinations of extensions and additions developed over the last 50 years, several are very important to understand if one treats by pathology, especially for functional hallux limitus, metatarsalgia, and posterior tibial tendinitis. Very little research is available on additions other than the metatarsal bar/pad and the reverse Morton's extension.

Functional hallux limitus has been accepted as the precursor pathology to the deformities of hallux valgus and hallux rigidus since it was first described by Pat Laird, D.P.M. in 1972 [8]. The contemporary concept is that some people have a decreased “stiffness” of their first ray which dorsiflexes in response to increased ground reactive force at the first metatarsal head, and this motion significantly decreases the dorsiflexion of the big toe joint. The purpose of an orthosis in this pathology is to reverse this by raising the medial column of the foot and plantarflexing the first ray. The reverse Morton’s extension is an addition to custom orthoses that will dramatically decrease the ground reactive force under the first metatarsal head and allows the first ray to plantarflex and give greater range of motion to the hallux. This is a proven technique in non-sport experiments [3]. The reverse Morton’s extension on a functional polypropylene device with a 4 mm medial skive is now classified as the pathology-specific functional hallux limitus orthotic device.

Posterior tibial tendon dysfunction (PTTD) or adult acquired flatfoot (AAF) following sports injury to this tendon has been successfully treated with foot orthoses. A study noted that in some cases the CFO worked as well as an AFO brace [9]. The orthoses stabilized the rearfoot and medial longitudinal arch in patients with chronic PTTD. A common complication of treating PTTD or AAF is the pressure placed under the navicular tuberosity by the rigid plastic of the orthosis resulting in pain. An addition called a sweet spot seems, in most cases, to solve this complication and reduce or eliminate the pain at this region in the medial longitudinal arch. A sweet spot is an orthotic implant of poron that is depressed into the body of the orthosis, while the plastic is still hot. This creates a soft cushion exactly where the navicular tuberosity touches the device. The clinician marks the area of the foot with a transfer marker, which identifies the area on the cast and allows the lab to implant the poron disk, of any size, in the exact area. This is also a useful pathology-specific addition for other problems like plantar fibromas and painful scars. The sweet spot can be placed wherever the clinician can draw a circle and be of any size, without disrupting the strength or integrity of the device.

The previously mentioned orthotic materials, construction technique, additions, and modifications obviously must vary according to age, sport, and intensity of the individual. Orthotic therapy for the athlete may have become more pathology specific in the literature, but because of the variations of age and sport, a great deal of the decision-making is left to the clinician with little evidence data to confirm any predictions of effectiveness.

So much remains unknown, even just considering orthosis flexibility. An average running sport requires 1,000 foot strikes per mile [10]. The time of full foot strike is calculated in 60th’s of a second and is the only moment in time during the mile when the orthosis is effective. It is a very brief moment for the orthosis to have an effect but according to many reports the positive effect on symptoms is more common than not.

Focusing treatment on a specific pathology rather than on a deformity can significantly improve clinical outcomes. An understanding of the pathomechanics that produced the athlete’s symptoms allows the clinician to address the needs of the athlete more specifically and construct an orthosis more effectively. Considering the material flexibility, advanced positive cast modifications, posting, and special additions will enable the sports practitioner to make a better orthosis for the athlete. A prefabricated orthosis meets some of the needs of all patients. A generic orthosis meets some of the needs of all pathology. But a pathology-specific custom foot orthosis should meet all the needs of a particular patient with a particular pathology.

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Ankle Foot Orthoses for the Athlete

13

Douglas H. Richie Jr.

Introduction

Ankle braces have emerged as a standard therapeutic modality in the treatment of the athlete. Over the past 30 years, more research has been published studying the treatment effects of ankle braces than any research on foot inserts or foot orthotics. Still, there remain many misconceptions and questions about the use of bracing of the athlete. This chapter will provide an overview of the types, indications, and effects of braces used in the lower extremity.

Terminology

An orthosis is an apparatus used to support, align, prevent, or correct deformities or to improve the function of moveable parts of the body [1]. The term brace is essentially synonymous with orthosis. The term "orthotic" is an adjective, i.e., "orthotic therapy" or "orthotic device." Yet, today most dictionaries list both an adjective and noun usage of the term orthotic, and consider an orthotic to be synonymous with the term orthosis.

An ankle foot orthosis (AFO) is any orthosis that covers the foot, spans the ankle joint, and covers the lower leg [2]. Thus, many popular ankle braces in use today would not qualify as true ankle foot orthoses simply because they do not cover a significant area of the foot.

Thus, for this chapter, the term ankle foot orthosis will apply to the preceding definition while the term ankle brace will be used to describe an orthosis which covers a portion of the leg and spans the ankle joint, but which does not cover or support

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a substantial portion of the foot. The term “prophylactic ankle stabilizer” (PAS) is also found in the medical literature and should be considered synonymous with the term “ankle brace.”

Types of Ankle Braces and Ankle Foot Orthoses

Ankle braces fall into three general categories. *Lace-up or gauntlet style braces* are usually made of canvas or nylon material (see Fig. 13.1). Additional stabilizers made of metal or plastic are often provided which can be added to special pockets in the medial or lateral side of the gauntlet. *Stirrup ankle braces* comprise semirigid plastic uprights which are oriented along the distal fibula and tibia and extend across the ankle joint to the medial and lateral aspect of the body of the calcaneus (see Fig. 13.2). Thus, stirrup ankle braces are also commonly referred to as *semirigid ankle braces*. The uprights are usually connected by a nylon strap which extends under the heel. The leg portion of the uprights are secured with velcro straps in multiple locations. The limb uprights are usually padded with either air bladder, gel bladder, or foam material. Stirrup style ankle braces can also be custom fabricated from plaster or other moldable materials for short-term use by the athlete.

A newer variation of the standard ankle stirrup brace is the *articulated stirrup brace*. Here a hinge connects a foot plate to the limb uprights at the level of the ankle joint (see Figs. 13.3 and 13.4). The foot plate of an articulated stirrup ankle

Fig. 13.1 *Lace-up or gauntlet style braces* are usually made of canvas or nylon material. (Courtesy of Swede-O Inc., North Branch, MN)

Fig. 13.2 *Stirrup ankle braces* comprise semirigid plastic uprights which are oriented along the distal fibula and tibia and extend across the ankle joint to the medial and lateral aspect of the body of the calcaneus. (Air-stirrup ankle brace, Aircast, courtesy of DJO, Inc., Vista, CA)

Fig. 13.3 A newer variation of the standard ankle stirrup brace is the *articulated stirrup brace*. Here a hinge connects a foot plate to the limb uprights at the level of the ankle joint. (Courtesy of Swede-O Arch Lok, Swede-O Inc., North Branch, MN)

Fig. 13.4 (**a**–**c**) Ambulatory ankle foot orthoses can take the form of both a custom and a non-custom (prefabricated) device. Prefabricated ankle foot orthoses include walking boots, solid and posterior leaf spring AFOs, and articulated AFOs with ankle joints. (**a**, **b**) Photos courtesy of Ossur Americas, www.ossur.com; (**c**) courtesy of Douglas H. Richie, Jr., D.P.M.)

brace does not cover a substantial portion of the foot; usually extending from the heel to the proximal arch.

Ankle foot orthoses can take the form of both a custom and non-custom (prefabricated) device. There are prefabricated AFOs gaining popularity for use in a non-ambulatory setting known as *night splints*. These devices are primarily used to prevent contracture of the gastrocnemius-soleus or the plantar aponeurosis during sleep.

Ambulatory ankle foot orthoses can take the form of both a custom and non-custom (prefabricated) device. Prefabricated ankle foot orthoses include *walking boots, solid and posterior leaf spring AFOs, and articulated AFOs with ankle joints* (see Fig. 13.5). Custom ankle foot orthoses can also use a solid and posterior leaf spring design, while articulated custom AFOs are generally a more preferred device for the active, athletic patient.

Virtually all ankle braces and AFOs are worn outside the sock of the athlete. In many cases, the sock is vital in providing protection of the integument from friction and pressure of the orthosis. At the same time, compared to athletic taping, the ankle orthosis is usually never in direct contact with the skin which may compromise sensory stimulation and proprioceptive benefits.

Treatment Effects of Ankle Braces and Ankle Foot Orthoses

Studies of Kinetics and Kinematics of Ankle Braces

Most studies of ankle bracing have focused on the kinematic effects, or change in range of motion of the joints of the ankle and hindfoot. In most cases, these investigations have compared various braces, or have compared the results of bracing to

Fig. 13.5 Custom ankle foot orthoses can also use a solid and posterior leaf spring design, while articulated custom AFOs are generally a more preferred device for the active, athletic patient. (The Richie Brace, courtesy of Douglas H. Richie Jr., D.P.M.)

athletic taping. Kinetic studies have focused on changes in ground reaction forces as well as displacement of center of pressure.

Kinematic studies have employed various methodologies which explain conflicting outcomes. In scrutinizing these studies, it is important to note if healthy vs. injured subjects were studied. In some cases, subjects were evaluated soon after an ankle sprain, while other studies involved subjects with a history of chronic ankle instability. The majority of studies, however, utilized healthy, non-injured subjects.

When effects on range of motion of the ankle are studied, confusion may arise from the use of terminology. Most kinematic studies of ankle bracing measure effects on "ankle joint" range of motion. The axis of motion of the ankle joint, as originally proposed by Inman [3], is primarily a dorsiflexion/plantarflexion axis allowing almost pure sagittal plane motion. The subtalar joint axis, described by Manter [4], is an inversion/eversion axis, allowing motion primarily in the frontal plane. Thus, when kinematic studies document reduced inversion of the calcaneus, when wearing an ankle brace, the effects of the brace were really at the level of the subtalar joint, rather than the ankle joint. Other studies have measured effects of ankle braces on talar tilt, which is a true measurement of ankle joint inversion/eversion.

Finally, kinematic studies may measure displacement of the ankle during passive movements or during dynamic movements. Studies utilizing passive motion devices vary in terms of position of the ankle in either a plantarflexed or dorsiflexed position. There is mounting evidence that ankle braces affect the ankle differently, depending on the sagittal plane position of the ankle. Dynamic studies simulating real sport movement, such as cutting maneuvers, may be more accurate methodology for assessing effects of ankle bracing.

Early studies of the effects of taping the ankle involved the use of varus stress radiography to measure changes in joint stability. Vaes and Lofvenberg used this technique to demonstrate that tape and a thermoplastic orthosis would be able to significantly reduce talar tilt [5, 6]. However, Vaes showed that the protective effects of taping reduced with exercise [5].

Similar results of taping were demonstrated by Gross [7]. Both taping and an Aircast stirrup significantly limited passive inversion and eversion of the ankle, but this range of motion increased after exercise in the tape group only. Greene and Hillman also compared the results of ankle taping to a semirigid ankle brace [8]. Again, both interventions significantly reduced inversion and eversion of the ankle. After 20 min of exercise, the taping intervention demonstrated a 40% loss of stability, which was not seen in the braced condition. Further studies have validated the finding that tape looses its ability to restrict ankle joint range of motion after as little as 10 min of exercise [9, 10].

Shapiro et al. studied the role of footwear on the effectiveness of taping and bracing the ankle in a cadaveric study [11]. High-top shoes alone and these same shoes combined with taping or bracing significantly improved resistance to ankle inversion compared to the low-top shoe. There was no difference between taping and any of the eight different braces studied.

Ashton-Miller et al. also studied the role of shoe design and found that a three-quarter-top upper allowed an athlete to develop an additional 12% voluntary resistance to inversion moment compared to a low-top shoe [12]. Also, a similar improvement was seen when the subjects wore a lace-up style brace, air-stirrup, or athletic tape. No differences were found among the protective devices.

Vaes et al. used an interesting dynamic measurement technique to determine both the speed and magnitude of talar tilt in a braced and unbraced condition [13]. Patients with functional ankle instability demonstrated significant decreased range and velocity of talar tilt during a simulated sprain when wearing an air-stirrup ankle brace. A slower velocity of inversion was proposed to be an advantage for the athlete, giving more time for muscular activation to prevent a sprain.

Podzielny and Henning also studied restriction of inversion (supination) velocity with four different ankle braces, compared to the unbraced condition [14]. A “supination platform” was used to induce sudden ankle perturbation. Three of the ankle braces reduced overall supination range and supination velocity. No differences were found in plantar pressure distribution patterns.

Further kinetic studies of ankle bracing were conducted by Cordova (Armstrong) [15]. Ankle bracing did not change ground reaction forces during lateral dynamic movement. However, ankle bracing did reduce EMG activity of the peroneus longus during peak impact force.

Siegler et al. were among the first to investigate kinematic changes induced by ankle braces in all rotational directions [16]. Four braces (Ascend, Swede-O, Aircast, and Active Ankle) were studied to determine angular displacement of the segments of the ankle joint complex in three body planes with six degrees of freedom. The authors discovered that significant differences existed among the braces in terms of limitation of inversion–eversion, internal–external rotation, and plantarflexion–dorsiflexion.

Conflicting results of previous studies showing restriction of inversion with ankle bracing were reported by Simpson et al. [17]. Kinematic data were collected from 19 subjects with previous history of ankle sprain during lateral cutting movement. Compared to wearing any of three different ankle braces (AirCast, Malleoloc, or Swede-O), the no-brace condition had a lower amount of ankle inversion. The authors speculated that the subjects may have used injury avoidance behavior in the no-brace condition in order to prevent ankle inversion.

Gudibanda and Wang performed a similar study to Simpson, evaluating ankle position during cutting maneuvers, but using healthy subjects [18]. These investigators found that the ASO lace-up strap reinforced brace did reduce maximum ankle inversion angle by 48% during forward lateral cutting which was significant. However, sideward lateral cutting, decreased inversion angle was only 3% with the brace which was insignificant. Also, the ASO brace decreased ankle plantarflexion angle significantly, by over 40% during both cutting maneuvers. The authors suggested that a reduced ankle plantarflexion angle was advantageous in reducing ankle sprain, citing previous studies by Wright and Neptune who showed that increased ankle plantarflexion resulted in decreased supination torque necessary to cause an ankle sprain [19]. Finally, ankle dorsiflexion was not affected by the ankle brace which the authors concluded would allow normal energy absorbing capacity of the ankle musculature.

Cordova et al. published a meta-analysis of 19 previous published studies comparing three types of ankle support (tape, lace-up, and semirigid) and kinematic changes before and after exercise. It should be noted that only studies of healthy, non-injured subjects were included [20]. The semirigid ankle brace provided the most significant restriction of ankle inversion initially and after exercise. After exercise, the semirigid ankle brace provided an overall decrease of ankle inversion by 23° compared to the control condition. Conversely, the tape and lace-up conditions lost support over time, resulting in an overall restriction of inversion by 12° and 13°, respectively. For ankle joint eversion, the semirigid device was again more effective in reducing motion than either tape or a lace-up brace. Dorsiflexion and plantarflexion range of motion was not affected by the semirigid condition but was most affected by the tape condition compared to the lace-up condition. Taping significantly decreases ankle joint dorsiflexion compared to a lace-up brace and a semirigid brace.

Nishikawa et al. studied shifts of center of pressure and foot pronation–supination angle in 12 healthy subjects in four conditions (semirigid, lace-up, taping, and no brace) [21]. Both the lace-up and taping conditions were associated with greater pronation angle during static stance. During gait, the center of pressure was more laterally displaced with the lace-up and taping condition, increasing the ankle joint moment arm for pronation.

Eils and Rosenbaum studied subjects wearing ten different models of ankle braces during free fall and maximum inversion during a trapdoor ankle perturbation maneuver [22]. Differences in the braces were found in maximum inversion angle which were dependent upon restriction of inversion velocity during free fall.

Spaulding et al. measured kinetic and kinematic variables in ten healthy subjects and ten subjects with chronic ankle instability [23]. Differences were noted in both kinetic and kinematic parameters between the two groups while walking on a level surface, up a step and up a ramp. There were no changes when the subjects wore ankle braces. The authors concluded that ankle braces did not alter selected gait parameters in individuals with chronic ankle instability.

Omori et al. performed a cadaveric study to determine the effects of an air-stirrup ankle brace on the three-dimensional motion and contact pressure distribution of the talocrural joint after lateral ligamentous disruption [24]. After severing of the lateral collateral ankle ligaments, inversion and internal rotation of the talus occurred. Application of the ankle brace only restored inversion displacement, not internal rotation. High pressure developed on the medial surface of the talar dome after ligament sectioning which was not corrected with the ankle brace. The authors concluded that the stirrup ankle brace functions to primarily restrict inversion. They also point out that ankle sprains also have a component of plantar flexion and internal rotation which are not controlled by this type of brace.

The role of footwear and its effect on performance of an ankle brace was studied by Eils et al. [25]. While an air-stirrup, lace-up, and taped condition significantly reduced passive ankle joint motion when worn in a shoe, this support was significantly compromised in the barefoot condition with the air-stirrup only. The authors recommended a lace-up brace for activities which involve a barefoot condition such as gymnastics and dance.

Studies of Ankle Foot Orthoses: Kinetics and Kinematics

Kinetic and Kinematic effects of ankle foot orthoses have been extensively studied [26–30]. However, most of this research has focused on the effects of ankle foot orthoses on patients with neuromuscular conditions. Few reports have been published on the effects of ankle foot orthoses in healthy subjects, and virtually no studies have been conducted on sport applications of these types of devices.

Kitaoka et al. studied the kinetic and kinematic effects of three types of ankle foot orthoses in 20 healthy subjects walking over ground [31]. In the frontal plane, all three orthoses (a solid AFO with footplate, solid AFO with heel portion only, and articulated AFO with footplate) all significantly reduced maximal hindfoot inversion, but did not affect eversion. The solid ankle AFO design significantly reduced both plantarflexion and dorsiflexion of the ankle, while the articulated ankle AFO did not affect ankle sagittal plane motion compared to the unbraced condition. Midfoot motion was reduced with the articulated AFO, and increased with the solid AFO. Cadence was reduced with the solid AFOs. All three braces were associated with decreased aft and medial shear forces compared to the non-braced condition.

Radtka et al. studied the kinetic and kinematic effects of solid and hinged (articulated) ankle foot orthoses on 19 healthy subjects during stair locomotion [32]. A unilateral hinged ankle foot orthosis produced kinematic and kinetic effects which were similar to subjects wearing no orthosis. The unilateral solid ankle foot orthosis produced more abnormal ankle joint angles, moments, and powers and more proximal compensations at the knee, hip, and pelvis than the hinged AFO during stair locomotion. Subjects wearing either orthosis walked slower during stair locomotion compared to the non-braced condition.

Hartsell and Spaulding measured passive resistive torque applied throughout inversion range of motion of the ankle in healthy subjects and those with chronically unstable ankles [33]. A hinged semirigid non-custom ankle foot demonstrated significant increased passive resistive inversion torque forces and restricted overall inversion motion better than a lace-up ankle brace.

In summary, the kinetic and kinematic effects of ankle bracing have been well studied with consistent results in several areas. Most ankle braces and ankle foot orthoses have been demonstrated to have an ability to restrict ankle joint inversion. Some braces affect ankle joint eversion, and little data is available to determine the effects of bracing the ankle in the transverse plane. In the sagittal plane, significant restriction of range of motion of the ankle joint and the midfoot can be accomplished, depending on the design of the brace, or use of simple taping.

What remains obscure is an understanding of the optimal range and plane of motion controlled by an ankle orthosis to achieve a desired treatment effect. There are clear indications that restriction of motion of any joint in the lower extremity will have negative effects in the neighboring joints, both proximal and distal. Of concern for the athlete is the effect of bracing on overall lower extremity function and sports performance.

Effects of Ankle Bracing on Sports Performance

Many forms of sport combine elements of running, jumping, and side-to-side movements. Speed and power of these movements are dependent upon an intact lower extremity which has efficient muscle firing and transfer of moment to the various joints for motion, and subsequent displacement of the body to an intended direction. The range of motion and alignment of the joints of the foot and ankle are critical to the efficient movement of the entire body. Limitation of motion of any joint of the hindfoot complex could be an advantage if excessive motion were available. Conversely, limitation of motion could potentially have negative consequences if a joint is restricted to a less than optimal range.

Thus, many studies have been undertaken to determine the effects of bracing and taping on overall athletic performance. As seen in kinematic studies, performance studies of ankle bracing lack consistency in methodology and have given conflicting results.

One of the first studies of performance and ankle bracing was conducted by Burks et al. [34]. Thirty healthy collegiate athletes performed four performance events: the broad jump, vertical leap, 10 yard shuttle run, and a 40 yard sprint. The tests were performed with both ankles taped, or with both ankles wearing two types of lace-up braces. The results were compared to the no-tape, no-brace condition. Half of the subjects perceived that at least one device decreased their performance. All three conditions significantly reduced vertical jump. Shuttle run was not affected by the braces, but was slowed by the taping. Broad jump was affected by only one of the lace-up braces, not by taping. Sprinting was affected by taping and one of the braces.

A different type of subject pool was utilized to study performance and bracing in a study by Hals et al. [35]. Twenty-five subjects who had recent acute ankle sprain but who had mechanically stable ankles with residual symptoms of functional instability were studied. Performance tests included a shuttle run and a vertical jump, with and without an Aircast stirrup brace. Use of the semirigid ankle support significantly improved shuttle run time, but not vertical jump performance.

Jerosch and Schoppe also studied subjects with functional ankle instability to determine the effects of a flexible strap style ankle brace on dynamic movements [36]. In a side step running test, the ankle support produced a significant faster time than the unbraced condition. In addition, the authors found no negative effect after 3 months of brace use in terms of isokinetic strength as well as speed of side step running.

Cordova et al. performed a meta-analysis of 17 randomized controlled trials which used a cross-over design to measure effects of bracing on performance measures [37]. The studies included comparison of tape, semirigid, and lace-up braces. Of these studies, approximately 30% used injured subjects. In terms of sprint speed, the largest effect was found with a lace-up brace, which yielded a 1% impairment. For agility speed, the net effects of all three supports was negative, but only 0.5%. For vertical jump, a 1% decrease in performance was found in all three conditions. The authors concluded that these negative effects are trivial for most individuals, but may have greater significance for elite athletes. They also recommended that the benefit of external ankle support in preventing injury outweighs the small negative effects on sports performance.

Balance and Proprioception

Athletes with functional instability of the ankle have been demonstrated to have deficits in balance and proprioception [38–41]. Restoration of proprioception has resulted in reduced frequency of ankle sprain [42]. Research has shown that lower extremity orthoses can have a positive effect on balance and proprioception.

Functional ankle instability consistently causes deficits in postural control [43–45]. Studies of foot orthoses have shown positive effects in improving postural control in both injured and non-injured subjects [46–53]. Mechanisms by which foot orthoses can improve postural control include optimizing foot position, reducing strain and load on supportive soft tissue structures, and improving the receptor sensory field on the plantar surface of the foot [54].

Neuromuscular control of the ankle relies on afferent input to the central nervous system. In the lower extremity, the somatosensory system provides this afferent input. This system includes the mechanoreceptors in the ligaments of the ankle, the cutaneous receptors in the feet and lower legs and the stretch receptors located in the muscles and tendons around the ankle.

Peroneal reaction time and postural sway are examples of an intricate reflex which includes sensory input (proprioception) and motor output. Since the output side of the reflex has multiple variables such as muscle activation time and muscle strength, looking at a performance task such as peroneal reaction time or postural sway does not actually isolate true proprioception. Measuring true proprioception is theoretically impossible, but measuring certain aspects of proprioception can give valuable information.

Studies of certain aspects of proprioception with taping or bracing subjects with previous history of ankle sprain have focused on either passive movement detection or joint position sense. Feuerbach et al. determined that the afferent feedback from skin and muscle around the ankle joint was more important than ligament mechanoreceptors in providing proprioceptive feedback [55]. Their studies on healthy subjects showed that a stirrup ankle brace significantly improved accuracy of ankle positioning tasks performed off weight bearing. Some studies have shown improvements of ankle joint position sense when ankle braces are worn [56, 57]. Other studies have reported no change or worsening of proprioception with taping and bracing [58, 59].

Raymond et al. conducted a systematic review of the literature and found eight high quality studies using controlled, cross-over design to measure either passive movement detection of joint position sense in subjects with and without taping of functionally unstable ankles [60]. Meta-analysis of the pooled results showed no improvements of proprioception when subjects with previous ankle sprain or functional instability were taped or braced. The authors concluded that while evidence exists for the protective benefit of bracing and taping the ankle, the reduction of risk of sprain is not likely due to enhanced proprioception.

Chronic ankle instability has been associated with delayed peroneal reaction time, which relies on proprioception as well as motor neuron activation [61, 62]. Karlsson showed that athletes with unstable ankles had significant delayed peroneal reaction time when tested on trap doors which could simulate inversion ankle sprains [63]. When the subjects were taped around the ankles, peroneal reaction time significantly improved.

Improvements of the peroneal stretch reflex with ankle bracing were verified in other studies of healthy subjects [64, 65]. However, another study by Shima et al. showed that ankle taping and bracing would delay the peroneal reflex in both normal and hypermobile ankles [66]. They speculated that the effects of external support would limit ankle inversion, and thus delay the peroneal stretch reflex.

Postural control is the ability of an individual to keep their center of mass within the borders of their base of support. It is a mechanism to maintain upright balance. The effects of ankle braces on postural control has been extensively studied. Baier and Hopf studied 22 athletes with functional instability of the ankle joint compared to 22 healthy athletes [67]. A significant improvement of postural control, as evidenced by reduced mediolateral sway velocity was found in the instability group when wearing both a rigid and semirigid stirrup ankle brace. However, other studies, performed on both healthy subjects and on subjects with functional ankle instability have failed to show any improvements of postural control with the use of ankle braces [68–71].

Studies of effects of ankle foot orthoses on balance have been performed on neurologically impaired subjects, and have not been performed on athletes [72, 73]. Cattaneo et al. showed that AFOs would improve static balance in patients with multiple sclerosis, but would compromise dynamic balance during gait [73].

In summary, studies of effects of ankle orthoses on balance and proprioception do not provide consistent findings. Yet, studies of treatment effects of these devices commonly conclude that any positive findings must be attributed to improvements in proprioception. In the final section of this chapter, several studies show the protective benefit of preventing the incidence of ankle sprains in subjects wearing ankle braces. While the incidence of sprains was clearly reduced, the severity of the sprain was not affected. Thus, a mechanical restraint of ankle rotation did not occur, whereas a proprioceptive influence possibly prevented the event itself.

As with previous studies, investigations of proprioceptive effects show varied results because of the various types of subjects (injured vs. non-injured, vs. symptomatic) and the methodology employed (static stabiliometry vs. dynamic posturography). Furthermore, ankle orthoses have not demonstrated the consistent improvements in postural control which have been previously demonstrated with foot orthoses in healthy subjects and subjects with chronic ankle instability. Further research is needed to determine the role of support of both the foot and the ankle in the treatment of athletes with chronic ankle instability.

Treatment of Injury

Ankle braces and ankle foot orthoses are commonly used in the treatment of injuries of the leg, ankle, and foot. There is no uniform consensus about the timing, selection, and criteria for use of ankle braces or ankle foot orthoses in the management of lower extremity injury.

Acute tears of the lateral ligaments of the ankle are best treated non-surgically with a functional rehabilitation program [74, 75]. Functional treatment of an ankle sprain utilize early mobilization of the ankle joint to stimulate healing and improve the strength of ligaments after injury [76, 77]. Ankle braces have been recommended as a simple way to provide protection for the ankle after acute sprain, while allowing easy removal for range of motion exercises [78, 79]. A systematic review of nine RCTs concluded that a functional rehabilitation program combined with a semirigid ankle brace is a preferred method to treat the acute ankle sprain compared to a functional program using an elastic bandage or tape [80]. The semirigid brace most often tested in these trials was an air-stirrup brace.

Some researchers have suggested that simple ankle braces do not effectively stabilize the ankle after acute ligament injury, and long-term functional complaints can occur if weight bearing is allowed too early while wearing these devices [81–83]. Glasoe et al. recommend that a more protective "immobilizer boot" (i.e., prefabricated plastic ankle foot orthosis, supporting the entire lower leg and foot, with soft liner and velcro closures) be used for initial weight bearing in the treatment of GradeII and Grade III ankle sprains [84]. This report, as well as others advocate early weight bearing, with protection around the ankle, to increase stability and stimulate ligament repair [85].

A more recent RCT evaluated three methods of immobilizing a severe Grade III ankle sprain: a short (10 day) period of strict immobilization in a cast, a removable walking boot (Bledsoe®) and a semirigid ankle brace [86]. The patients who were immobilized in a cast had less pain and swelling at 3 months post injury. These results suggest that immobilization may be critical during the initial inflammatory phase of collagen repair. However, immobilizing with a removable walking boot did not achieve the desired benefits because it had the lowest compliance of all three interventions of compliance issues. Furthermore, this study did not include a supervised functional rehabilitation program.

A head-to-head comparison of a walking boot versus an air-stirrup brace to treat Grade 3 lateral ankle ligament injuries was conducted in a randomized controlled trial [87]. A functional rehabilitation program was provided to both groups of patients. The patients treated with the brace had a faster recovery, earlier return to work and better functional scoring that the patients treated with a walking boot. Compliance with either device was not reported.

The evidence supports the use of a semirigid ankle brace to treat moderate to severe ankle sprains [88]. Taping can achieve similar results as bracing but patient comfort and satisfaction has found significant advantage to bracing compared to taping [89]. Walking boots have not been studied nearly as much as semirigid ankle braces in the treatment of acute ankle injuries. While ankle bracing combined with a functional rehabilitation program has been the favored treatment of ankle sprains, the high rate of long-term sequelae and failure to recover has caused clinicians to turn to more restrictive forms of immobilization when treating this injury.

Prefabricated ankle foot orthoses such as walking boots appear to provide necessary protection of the ankle after acute ligament injury to allow early weight bearing, without the potential negative results that could occur with simple ankle bracing. In addition, these “walking boots” have been shown to be as effective as a cast in reducing soleus and peroneal muscle activity during the stance phase of gait, while actually significantly reducing gastrocnemius activity compared to a cast [90]. Thus, a walking boot may be preferred compared to a cast, in the management of trauma to the tendo achilles.

Progression from a walking boot to an ankle brace should occur sometime during the rehabilitation program for treatment of the ankle sprain. There is no consensus of opinion about the timing of this progression, and there are no accepted objective criteria for when to institute and discontinue bracing of the ankle during the recovery process. Since complete maturation of collagen does not occur until 9–12 months after ligament injury, many authorities advocate the use of some type of external orthosis for the treatment of ankle sprains until complete recovery has been attained [91].

Ankle foot orthoses are being increasingly utilized, in favor of traditional ankle braces, in the treatment of tendinopathy of the ankle, degenerative arthritis of the ankle, and midfoot sprains [92]. Simultaneous control of both the ankle and subtalar joint make ankle foot orthoses more suitable than ankle braces for the treatment of peroneal tendon injuries and posterior tibial tendon dysfunction [93]. In addition, ankle foot orthoses have demonstrated better recovery from syndesmosis sprain than a traditional lace-up ankle brace [94].

Prevention of Injury

The ankle sprain is the most common injury in sport, comprising at least 20% of all traumatic episodes affecting athletes [95]. Evidence suggests that there is a twofold increased risk of recurrent sprain after a first-time ankle sprain [96, 97]. Ankle bracing and neuromuscular training have both been recommended as being effective in reducing the risk of recurrent sprain by at least 50% [98].

Two studies have compared the effectiveness of a semirigid ankle brace compared to neuromuscular training in preventing recurrent ankle sprains. A randomized three-arm controlled trial of 384 athletes who had experienced an ankle sprain showed a 47% reduction of recurrent sprain with ankle bracing compared to neuromuscular training [99]. Compliance was better with the bracing intervention than the training program. Another three-arm randomized controlled trial of 340 athletes found that bracing was found to be the superior intervention to prevent recurrent ankle sprains over both neuromuscular training and the combination of both measures, providing a more effective and less expensive treatment [100].

Several studies have validated the role of ankle braces to prevent sprain in various sports. However, the mechanism by which ankle braces and AFOs achieve positive treatment outcomes for ankle injury remains speculative despite a large volume of research on this subject. The role of shoe design and athletic taping in basketball players was studied by Garrick and Requa [101]. The combination of a high-top shoe with taping reduced ankle sprains fourfold compared to standard shoes with no taping.

Rovere et al., in a retrospective study, compared the effects of tape to a lace-up brace in the prevention of ankle sprains in football players [102]. The lace-up brace was associated with one-half the number of ankle injuries as the taped condition.

Two prospective studies have been published comparing the effects of an Aircast splint to the non-braced condition in the prevention of ankle sprains. Sitler et al. followed 1601 cadets at the United States Military Academy while playing basketball over a period of 2 years [103]. There were 46 ankle injuries to this group during the time period, of which 35 occurred in the non-braced group. The braced group experienced 11 injuries, revealing a threefold increase incidence of sprain in the non-braced group. There was no statistical difference in injury rate comparing those athletes who had been previously injured prior to the study vs. those who were not. The severity of ankle sprain was not different in the braced vs. non-braced groups.

Surve et al. studied 504 soccer players randomized into two groups, braced with an Aircast vs. no brace, and followed for an entire season [104]. The use of an air-stirrup brace reduced the incidence of ankle sprain by nearly fivefold, in the previous injured group of athletes only. The brace did not significantly affect injury rate in those athletes who had not been injured prior to entering the study. The severity of sprain was also significantly reduced with use of the brace in the injured subjects only. Thus, the benefits of the ankle orthosis was limited to those subjects with a previously sprained ankle.

Both studies by Sitler and Surve showed no increased incidence of knee injuries when wearing ankle brace. Sitler showed that bracing would not prevent severity of sprain, only incidence of sprain. They speculated that ankle bracing did not achieve its benefit by restricting joint range of motion, but rather by facilitating proprioception. Conversely, Surve showed a preventive benefit in severity of sprain by use of an ankle brace, but only in previously injured subjects.

Olmstead et al. conducted a numbers needed to treat analysis of three previous studies (Garrick, Sitler, Surve) to determine the cost-benefit of taping vs. bracing in the prevention of ankle sprains [105]. To prevent ankle sprains over an entire season, taping was found to be three times as expensive as bracing. This cost was based upon supplies alone; the labor cost of repeated application of tape by the trainer was not included. The authors concluded that taping and bracing appear to be more effective in preventing ankle sprains in athletes with a history of previous sprain. Furthermore, the superiority of taping vs. bracing in preventing injury has yet to be proven, but the cost-benefit analysis clearly shows an advantage for bracing.

The question of the benefit of preventive ankle bracing of healthy high school athletes has finally been answered with two high quality randomized controlled trials. McGuine and coworkers studied 1460 male and female high school basketball players during an entire season and found that a lace-up ankle brace reduced the incidence of first-time ankle sprains by threefold compared to the unbraced condition. The protective effect of wearing the brace occurred in athletes both with and without previous ankle injury. Furthermore, the incidence and severity of knee injuries was not affected by wearing the brace [106].

In another randomized controlled trial, McGuine and coworkers studied 2102 male high school football players during a full season. A lace-up ankle brace again reduced the incidence of ankle sprain by over 60% in both previous injured and non-injured players. The incidence and severity of knee injuries was not affected by wearing an ankle brace [107].

Summary

1. Ankle braces have been thoroughly studied to determine the kinematic and kinetic effects on both injured and healthy subjects. These braces can limit the range and velocity of inversion, with less effects on eversion and plantarflexion.
2. Compared to tape, ankle braces are less likely to loose supportive benefit during exercise. Braces are more cost effective than tape when used to prevent ankle sprains.
3. The effects of bracing on athletic performance are minimal and do not preclude the use of these devices for the prevention or treatment of injury.
4. There is some evidence that ankle braces will improve proprioception and sensory feedback, although studies of postural control do not show as positive of outcome as similar studies with foot orthoses.

5. Ankle braces may not provide enough restriction of motion and support around the ankle joint for the immediate treatment of severe ligament injury of the ankle. Solid short leg walking boots (ankle foot orthoses) are preferred for this intervention.
6. Ankle foot orthoses support and control rotation of both the subtalar and ankle joints and appear better suited for treatment of tendinopathy of the foot and ankle.
7. Ankle braces have demonstrated a preventive effect for ankle sprain in adult subjects with previous sprain, and will likely prevent an ankle sprain in healthy high school athletes.

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Insights on Prescribing Athletic Footwear and Orthoses: The Game Plan

14

Matthew B. Werd and E. Leslie Knight

This textbook is designed to assist sports medicine professionals to provide an appropriate research-based prescription for athletic footwear and orthoses, with the goal of maximizing athletic performance and minimizing injury. Often neglected, overlooked, or misunderstood, the athletic shoe gear prescription should be the *first* step in the lower extremity treatment of the athlete. Overwhelming evidence is now available and has been presented throughout this text, which supports the appropriate use of custom foot orthoses in the athlete.

As the athletic shoe industry continues to evolve, it is critical for the sports medicine practitioner to keep up to date with the newest technologies, terminology, and trends. The American Academy of Podiatric Sports Medicine (AAPSM, the Academy) has been a reliable, unbiased source for contemporaneous information on athletic footwear, and is referenced throughout this chapter and book [1].

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AAPSM no longer rates, reviews, or recommends specific athletic footwear. The Academy has published an important detailed explanation regarding footwear testing, reviews, and limitations. The following is excerpted from the www.AAPSM.org web site, which provides some helpful insight on shoe evaluations and reviews [1]:

"*In January 2010 the AAPSM Board voted to discontinue the process of reviewing, rating or recommending footwear. To date there has not been a reliable, repeatable methodology of footwear assessment that meets the standards of evidenced based medicine. For that reason the AAPSM Board felt it was disingenuous to engage in the practice of testing footwear and making recommendations based on those tests. One of the main goals of the AAPSM is to serve as an authoritative source of educational material for both the public and medical professionals.*

Athletic shoe fitting is a process that must be done one-on-one with an experienced shoe fitter. Making shoe recommendations over the Internet or recommending one shoe over another for the masses is an exercise in futility. Footwear's effects on comfort and performance cannot be reliably predicted for an individual using current methods of testing. The ultimate test of any shoe is the individual experience that the user has with it. Because gait patterns, biomechanics and foot shapes are so unique, individuals have to understand that they are their own experts on footwear. The AAPSM will work to provide meaningful information for our readers so they can make informed choices but the bottom line is that the shoes must be worn and experienced in order to understand how they work for any given person.

Members of the AAPSM recommend that individuals be fit by a reputable footwear retailer and seek out a sports medicine podiatrist for concerns on injury or footwear. It is extremely difficult to accurately recommend footwear without assessing first hand, an individual's gait pattern, and range of motion, biomechanical profile and foot type. Other factors such as injury history, body mass index, weekly miles or hours of training, training goals, training philosophy, and training surface are all important in selecting the right shoe. These things cannot be done via the internet. While unreliable forms of self-assessment have been used elsewhere, we avoid advocating these means. Research has not validated wet paper towel tests, shoe wear patterns and the ability to rates one's own degree of pronation as reliable or meaningful in terms of biomechanics. In addition, weight-bearing balance measuring devices and treadmill analyses performed outside of a professional office setting may also not be predictive of footwear needs.

Some footwear and foot type information may be helpful to those who are overwhelmed with the abundance of footwear choices but the AAPSM suggests that individuals keep in mind these caveats:

Reliability of Testing Methodology
Research has not yet shown that current methods of testing footwear provide meaningful information in terms of injury prevention, performance or comfort. Even automated testing methods that use machines to simulate running or walking on the shoe are flawed because running shoes perform differently with a living human moving on top of the shoe.

User Reviews
The internet has provided a forum for individuals to rate shoes and post feedback on their experience. Shoes affect our comfort and performance on every step of every day and we all have different foot shapes, body types and gait patterns and we experience comfort in very unique ways. So while user reviews may be helpful in terms of quality and/or durability, they are irrelevant in terms of comfort or performance from one individual to another.

Forms of Assessment
A significant flaw in recommending footwear via the internet is that whoever (or whatever) is making the recommendation requires the individual to classify themselves according to

their level of pronation and their arch height. There are two problems with this scenario; unless one has been examined by a medical practitioner or has a slow motion video of themselves running barefoot then there is no way to accurately judge how much they pronate. Only a podiatrist or other sports medicine specialist can classify their range of motion and level of pronation. The second issue is that there is no agreed upon definition of what constitutes overpronation or even how much intervention may be necessary to manage it.

In terms of arch height, the wet paper test is commonly recommended as a simple way to assess arch height, which is assumed to be indicative of pronation level. However, the problems with this are that research has shown that arch height in a standing position is not a reliable means of assessing pronation and the test is done while standing but running and walking are dynamic movements in which the arch height changes from heel strike to toe off.

Shoe wear pattern has also been touted as a reliable means of assessment but it is a small part of a more thorough exam process and is, by itself, an inaccurate way of evaluating foot and ankle characteristics."

"Minimalist Index"

Formulating a reliable, useful rating system for evaluating athletic shoes has been an ongoing frustration and challenge for sports medicine professionals and athletes alike. A panel of 42 experts from 11 countries created in 2015 a novel minimalist shoe rating system called the "Minimalist Index" or "MI" [2]. This minimalist index was developed as a way to define minimalist shoes based on a numeric rating scale. This scale assesses several key minimalist shoe features, but we may potentially be able to apply and expand these concepts of objective rating to all athletic shoes.

The agreed upon definition for a minimalist shoe states, "Footwear providing minimal interference with the natural movement of the foot due to its high flexibility, low heel to toe drop, weight and stack height, and the absence of motion control and stability devices." The authors conclude, "This standardized definition of minimalist shoes developed by an international panel of experts will improve future research on minimalist shoes and clinical recommendations. MI's adequate validity and reliability will allow distinguishing running shoes based on their degree of minimalism, and may help to decrease injuries related to footwear transition" [2].

Key shoe features included in the MI rating scale include: *Flexibility*—the shoe is tested for longitudinal (forward part of the shoe is bent up) and torsional (forward part of the shoe is torsioned toward pronation) flexibility. The more flexibility, the higher the score on this subscale; *Weight*—The lighter the shoe, the higher the rating on this subscale of the Minimalist Index; *Stack height*—evaluates the distance between the center point of heel contact in shoe to the most external part of the outsole. The thinner the shoe, the higher the score on the stack height subscale; *Stability and motion control technologies*—identify the most commonly used technologies in running shoes to control pronation. The least amount of technologies in the shoe equates to a higher value on the Minimalist Index; *Heel to toe drop*—equals the difference in millimeters between shoe thicknesses under the heel versus forefoot. The closer to 0 mm drop, the higher the rating on the Minimalist Index.

"The Game Plan"

This chapter presents a systematic approach—the game plan—for prescribing athletic footwear and orthoses, incorporating all facets of shoe gear to ensure maximal effectiveness. Each component of the prescription for athletic footwear and orthoses is broken down and discussed in-depth in other chapters throughout this textbook. Please refer to the appropriate chapter for a more in-depth discussion of each component. Key features of the athletic shoe will be expounded in this chapter with a more detailed discussion of evolving terminology and technology.

A ten-point sequential guideline—protocol or checklist—customized for each athlete will be helpful in making decisions on each aspect of athletic footwear; however, it is ultimately up to the sports medicine practitioner to recommend which athletic shoes or which orthotic devices are most appropriate for each individual athlete. This protocol was adapted and updated from the original 15-point sequential guideline from the first edition of *Athletic Footwear and Orthoses in Sports Medicine* [3].

Protocol for prescribing athletic footwear and orthoses in sports medicine Ten components	
☐	1. Determine the *foot type* and *foot function during gait*
☐	2. Consider any *foot pathology* and *size and weight* of athlete
☐	3. Consider the athlete's *fitness level* and *demands from their sport*
☐	4. Assess *key features of the athletic shoe*
☐	5. Recommend *athletic shoes* and *referral to specialty athletic shoe retailer*
☐	6. Recommend *athletic socks*
☐	7. Recommend *athletic shoelaces* and *lacing techniques*
☐	8. Recommend *over-the-counter athletic shoe inserts prn*
☐	9. Recommend or referral for *athletic custom foot* or *ankle orthoses prn*
☐	10. Reevaluate for possible *modifications after wear testing*

1. Determine the foot type and foot function during gait

Foot type can be classified by the arch height, which will provide a starting point as to how the foot will function biomechanically during gait and to what level of pronation occurs in the foot, which may help determine which athletic footwear may be most appropriate. Historically, the "wet test" has been used as a quick and easy test for the lay athlete to determine arch type; however, this static test has not proven to be reliable or a clinically beneficial method of assessing or predicting the level of pronation. Either quantifying navicular drop or assessing the vertical forces beneath the foot during a dynamic evaluation can make a more contemporary and accurate determination of arch height and foot type.

The three basic categories of foot types are: low arch (flat foot), normal arch (neutral), and high arch (cavus foot). In general, a low-arched foot is more flexible and will function dynamically with increased pronation. A normal-arched foot will function with an appropriate amount of pronation. A high-arched foot is more rigid foot and will function dynamically with limited pronation.

Gait evaluation is an important part of an athletic evaluation. Static examination of an athlete's foot type is a good starting point; however, a dynamic evaluation will provide more information on how the foot functions in real time. Based on the dynamic function of the foot, a more appropriate recommendation can be made regarding the biomechanical needs of the athletic footwear and orthoses.

Clinical evaluation of the amount of pronation during gait can be subjectively assessed by visualizing the athlete walk and run (observational gait analysis); however, a more objective and accurate gait analysis can be performed using hi-tech video analysis and force-measuring platforms or in-shoe pressure-measuring technology. See Chap. 4 for more detailed information.

The amount of foot pronation noted during gait can be excessive, increased, biomechanically efficient, decreased, or absent (supinated). Examination of an excessively pronated foot during gait will demonstrate an internally rotated leg, an excessively everted calcaneus, a collapsing arch, and an excessively abducted forefoot.

It is important to observe not necessarily *how much* excessive pronation occurs, but *when the excessive pronation occurs* during the gait cycle.

A complete biomechanical examination should note any asymmetries starting with observation at the head and progressing distally to the shoulders, back, hips, knees and patella, legs, ankles, and feet. The amount of core strength and stability should also be assessed, as a weak core may predispose a lower extremity injury.

2. Consider any foot pathology and size and weight of the athlete

Common foot pathology which may affect the choice of appropriate athletic footwear and orthoses includes (but is not limited to) posterior tibial tendon dysfunction, spring ligament strain, metatarsalgia, plantar fasciosis, calcaneal apophysitis, hallux valgus, hallux limitus, sesamoiditis, stress fractures, neuromas, sinus tarsi syndrome, lateral ankle instability, peroneal tendon pathology, tarsal tunnel syndrome, and Achilles tendon pathology.

Lower extremity injury history and prior shoe experiences should be reviewed and discussed with the athlete. Review of leg, knee, hip, and back deformities should also be assessed.

Physical size of the foot and the weight of the patient must be considered when recommending athletic footwear and orthoses, as the foot size may affect proper fit of the shoe and may affect the choice of material and the size and thickness of a foot orthosis. Foot size can be categorized as being large, medium, or small and width being either wide or narrow. Shoe volume, width, and length must be adequate. Shoe and orthosis materials need to be sufficient to accommodate the athlete without breaking down prematurely.

3. Consider the athlete's fitness level and demands from their sport

The physical demands of an elite, professional, or Olympic caliber athlete will be different from that of an occasional weekend warrior. The elite athlete's training regimen will vary greatly compared to the training demands of a casual athlete, which needs to be part of the consideration when recommending athletic shoe gear.

Each sport has its own set of factors, which may affect the choice of appropriate athletic footwear and orthoses, including the types of movement necessary. For example, distance running requires straightforward heel-to-toe motion while tennis requires side-to-side and front-to-back movements on the ball of the feet.

A sport-specific show should be considered if more than 3 h/week are spent training in that sport. Sport surface also needs to be considered, whether it is a smooth court, a grassy field, artificial turf, or hard concrete.

4. Assess key features of the athletic shoe

Technologic changes to athletic footwear and orthoses occur rapidly; it is critical for the sports medicine specialist to understand and be aware of evolving terminologies, trends, and fads in order to educate the athlete regarding potential benefits and/or risks.

Running shoe selection during the first running boom of the 1970s was extremely limited and offered very few choices, features, or technology—as evidenced by Dr. Subotnick shown in Fig. 14.1 on the cover of *The Running Foot Doctor*, published in 1977—while a virtual explosion of athletic shoes, options, and technological features has occurred over the past 40 years.

There has been a shift in focus from using cushioned materials in the 1970s and 1980s, to using duel density materials and hard plastic devices to help “control motion” in the 1990s. Midsole materials are rated by durometer (hardness of material): the harder the midsole, the more supportive the shoe—this focus changed to using different durometer materials in different locations within the shoe in order to help guide the foot through gait more biomechanically efficient.

The term “motion control” is ubiquitous among athletic shoe manufacturers when referring to a shoe that is produced to limit excessive foot pronation and is thus referenced in this textbook as well; however, it may not be the most appropriate term. An athletic shoe material or technology does not actually “control” the motion of the foot, but it may have the effect to guide the foot through a more biomechanically efficient pathway.

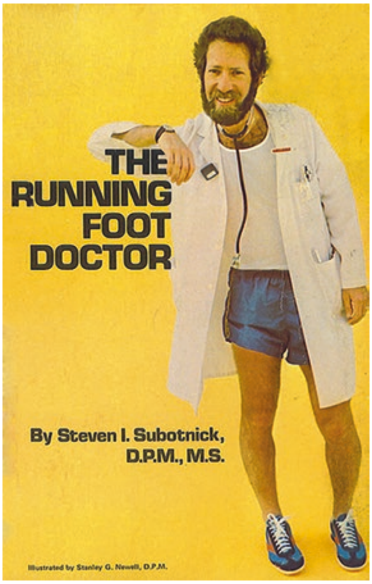

Fig. 14.1 Dr. Subotnick shown on the cover of The Running Foot Doctor, published in 1977, when running shoe selection offered very few choices, features, or technology

The once-popular trend toward barefoot and minimalist footwear and “natural running” has shifted in the opposite direction on the pendulum—toward producing shoes providing increased or “maximal” cushioning, lower ramp angles, changes in stitching of the upper, and even in changes to the geometry and construction of the midsole and outsole.

The term “preferred movement pathway” as proposed by Benno M. Nigg, Dr.sc.nat. Dr.h.c., and advanced by Australian sports podiatrist Simon J. Barthold, B.Sc. Fellow, AAPSM, has been previously presented in regard to the intended function of athletic shoes (Personal communication).

Objective features should be considered in a running shoe:

Objective features of a running shoe
Traditional athletic shoe components:
Last shape
Seams
Heel counter
Heel contact shape
Midsole cushion/firmness at heel lateral and medial
Forefoot and midfoot flexibility/stability
Midfoot torsion
Interior shoe volume
Toe box width
Insole
Evolving athletic shoe features:
Heel-to-toe drop (aka forefoot drop/ramp angle)
Stack height
Outsole geometry
Wrapping of outsole and midsole
Platform width
Midsole stiffness
Knitted upper

The sports medicine professional needs to become familiar with, and aware of, constantly evolving shoe features, as this knowledge will aid in the discussion and education of the athlete. Below are highlights of some of the evolving athletic shoe features.

Heel-to-toe drop (aka forefoot drop/ramp angle)
The ideal heel-to-toe drop is yet to be determined; is a zero-drop shoe appropriate for all athletes? Or, will some athletes function best in a traditional 10–12 mm drop shoe? Is it more efficient to add/remove more forefoot cushioning or to increase/decrease the heel cushioning in order to affect the heel-to-toe drop? Perhaps certain conditions or pathologies or even running styles may function better at differing ramp angles. See Figs. 14.2 and 14.3.

Also, practitioners prescribing foot orthoses must also consider the effect of and be cognizant of the increased ramp angle, created by adding an orthosis into an athletic shoe. If an orthosis has effect to *increase* the ramp angle, then is it beneficial to recommend an athletic shoe with a *lower* ramp angle in order to offset the effect of adding an orthosis?

Fig. 14.2 Traditional running shoe features; notice the standard heel-to-toe drop and dual-density midsole

Fig. 14.3 "Zero Drop" running shoe features; notice the level heel-to-toe drop (zero drop in height from the heel to the toe of the shoe) and single-density cushioned midsole

Fig. 14.4 Maximal-cushioned running shoe features; notice the slight heel-to-toe drop (drop in height from the heel to the toe of the shoe), maximal cushioned midsole, and outsole shoe geometry known as a "meta-rocker"

Research and future evidence will help address similar questions—and may even lead to new findings and technologies.

Stack height
Stack height is measured at the center of the heel as determined by the distance between the heel's contact point within the shoe and the most external part of the outsole of the shoe beneath. Traditional shoe stack heights have been 24 mm, while minimalist stack heights have been below 5 mm, and maximalist shoe stack height can approach 35 mm or greater. See Fig. 14.4.

Outsole geometry
Traditionally, outsoles have used flex grooves, but many newer shoes have begun to implement "fulcrum-themed" or "hinged" or "pivot" technology. Fulcrum-engineered outsole geometry is designed to give an advantage or head start to foot propulsion in the heel strike (or "plant") to propulsion (or "push off") phases of gait.

A rocker outsole incorporates a hinge type of effect and can be evaluated when looking at a shoe from the side view. A "meta-rocker" outsole and "lugs" incorporated under the forefoot are examples of this technology, while other shoes "pre-flex" the outsole, which provides a built-in hinge effect.

Questions remain as to how to best implement this "plant-to-push off" technology, i.e., what degree should the hinge be angled from heel-toe and from lateral-medial and what length is the ideal hinge platform?

Customization of flex grooves with 3D printers is in its infancy, but may become more frequent as manufacturing costs are reduced.

Midsole wrapping
Midsole wrapping is an emerging concept, which extends the midsole higher to encase (wrap) the upper, and it creates markedly enhanced stability, compared to traditional dual-density midsole technologies. This technique may eliminate the need for traditional technologies, which focused on adding higher density materials and hard plastic devices in the medial midsole. Base support is also widened with midsole wrapping and the heel of the foot is "sunken" into the midsole. The effect is for the foot to no longer function as being set *on top* of the midsole, but for the foot to now function cradled *inside* of the midsole, similar to what is referred to as a "bathtub effect." Lateral column motion control is also enhanced, as well as enhanced support for overpronation.

Platform width
Increased platform width of the midsole and outsole in the forefoot creates more stability to allow for higher stack heights. Gradual widening of the platform from a narrower heel to a wider forefoot provides more inherent stability.

Midsole stiffness
Traditionally, cutting out or "scalloping" the mid portion of the outsole and midsole, allowing more flexion at the midfoot, has *decreased* midsole stiffness. Increasing midsole stiffness provides a more rigid lever, compared to a more flexible midsole. Stiffness through the midsole will limit the amount or torsion or twisting from heel to toe. Also, a stiff midsole may provide additional stability to accommodate a custom foot orthosis.

Knitted upper
One-piece knitted uppers have an advantage—versus multi-material uppers—of eliminating the need to use multiple materials from multiple manufacturers, which often create overlapping of upper materials. These one-piece knitted uppers require highly technical manufacturing processes and are cost-limited, but may better address issues with shoe fit, as well as to improve performance.

5. **Recommend athletic shoes and referral to specialty athletic shoe retailer**
Developing a good working relationship with a local specialty athletic shoe store will help ensure that an athlete is fitted properly and selects comfortable shoes. The specialty running retailer can be an excellent source for keeping abreast of current and future technologies, terminology, trends, and fads.

Comfort and fit should be considered when recommending athletic shoes. Advise the athlete to discuss with the athletic shoe specialist: current and past injuries, prior history with select shoe types and brands. Also, it may be helpful for the athlete to bring older worn shoes to the athletic shoe retailer for evaluation. See Chap. 19 titled, "Specialty Running Stores and the Sports Medicine Professional: A Natural Partnership" for more information, and visit the *Running Industry Association*'s website for additional information and to find a member retailer by location [4].

The American College of Sports Medicine has published a brief brochure providing tips for athletic shoe selection, titled, "ACSM Information on… Selecting Running Shoes" [5].

6. **Recommend athletic socks**
Sport socks have evolved and many choices of materials, cushioning, and even sock length need to be considered, depending on the sport and application. Compression materials—as well as gradual pressure gradients—continue to emerge for both performance and recovery purposes.
7. **Recommend athletic shoelaces and lacing techniques**
Athletic shoelaces and lacing patterns are often not considered in the athletic footwear prescription, but should not be overlooked. Certain foot types and pathology may be improved by basic shoe re-lacing patterns, and shoe fit may be improved by using different shoelace materials and a multitude of high-tech lace-locking systems.
8. **Recommend prefabricated athletic shoe insoles**
Athletic shoe manufacturers invest very little technology in the inserts that come with shoes. Prefabricated athletic shoe insoles are helpful—in addition to the appropriate athletic shoe type—when additional cushioning, support, or stability features are required. These off-the-shelf devices are relatively inexpensive, semi-customizable, and easily modified.
9. **Recommend (or referral for) athletic custom foot or ankle orthoses**
Recommend (or referral for) custom foot or ankle orthoses is one of the final steps to be taken when all prior steps have not fully resolved the athlete's condition. Evidence overwhelmingly documents and supports the effectiveness of custom foot orthoses in sports medicine.

The type of custom foot orthoses prescribed is dependent on a multitude of factors—as addressed throughout this book. Custom foot orthoses have been proven to be an important adjunct in conservative care of the athlete, which function to decrease the risk of certain injuries and potentially enhancing athletic performance.

Ankle foot orthoses have been proven to be an important adjunct in conservative care of the athlete. The type of ankle foot orthoses prescribed is dependent on a multitude of factors (please see ankle foot orthosis chapter).

Athletic shoe modifications can further enhance athletic shoe fit and function, and should be considered for certain athletic conditions.

10. **Reevaluate for possible modifications after wear testing**
After each step above has been completed, a follow-up assessment of the athlete should be made after an adequate wear-test to assess effectiveness and to make modifications or adjustments if necessary. Follow this ten-point protocol and be assured of prescribing the most appropriate footwear for every athlete under your care.

Additional Insights…

Athletic shoe companies seem to have shifted their decades-long focus *from* trying to produce shoes with features to *accommodate* runners who do not run efficiently—*to* trying to produce shoes with features to *promote* runners to run properly.

"Smart shoes" which are equipped with sensors to communicate and stream real-time data—such as cadence, landing zone (foot strike), impact rate, ground contact time, and others—directly via Bluetooth to the athlete are currently available, but still in their infancy. Customizable shoes are also commercially available on a limited scale, but their market is certain to increase, as will the production of 3D printing of custom shoes.

"Smart socks" are becoming more available—in which socks are equipped with textile sensors embedded into the fabric of the athletic sock and are able to detect pressure and force data—measuring cadence, foot landing, and more. The thought behind these smart materials is to improve performance and detect injury-prone running style in real time.

The "minimalist" or barefoot trend evolved and provided newer terms such as "ramp angle" and "forefoot drop" and "zero drop" and "natural running." One benefit of this trend has been a renewed focus on proper running form, strengthening of the intrinsic foot muscles, and coaching of athletes to become more efficient runners. Also, the minimalist trend has spawned a new shoe rating system termed the "Minimalist Index (MI)." The MI may continue to be tweaked, and eventually be applied to a rating system for all athletic shoe categories.

Interesting to note, Grier et al. found that US Army soldiers who chose to use minimalist running shoes—versus those who chose to wear traditional running shoes—did not appear to be associated with higher or lower injury risk [6].

Altman and Davis compared the incidence rate of injuries between shod and barefoot runners and concluded that barefoot running is associated with fewer overall musculoskeletal injuries/runner, but similar injury rates [7].

The "maximalist" footwear trends continues to evolve and with it comes a host of new features and terminologies, such as "stack height" and "outsole and midsole geometry" and "platform width" as well as attention to an upper's knitting manufacturing process. Greater attention to shoe geometry has evolved from the maximalist trend, which may bring a new paradigm for the approach of stabilizing the unstable foot within the shoe.

Several newer athletic shoe innovations are still in their infancy, but exciting to consider. Beverly presented three of these innovations, which include “Circular knitting” in which a computer-controlled machine creates custom shapes and zones in a shoe’s upper that provide extra support or flex; “laser siping” works by cutting precision grooves into a traditionally molded sole, custom-altering flexibility, cushioning, and support; and “selective laser sintering” which uses a 3D laser printer to fuse powdered plastic into a finely detailed solid copy of the athletes footprint, allowing unprecedented control over shape and density [8].

Athletic Footwear and Injury Prevention

Sports medicine professionals must always keep in mind that *athletic shoe gear is just one factor* in a list of many factors contributing athletic injuries. Listed below are other contributing factors that must be considered when evaluating lower extremity athletic injuries:

Contributing factors to consider that may be associated with lower extremity athletic injuries:
– Athletic shoe gear
– Injury history
– Body Mass Index (BMI)
– Training surface
– Sport type
– Training hours per week
– Cross-training
– Running form and biomechanics
– Overuse
– Medical history
– Motivation of athlete
– Coaching
– Parenting

Nigg and Mundermann found that a key factor affecting injury rates in military personnel was shoe *comfort*. Individuals may have a “comfort filter” in which individuals tend to wear shoe gear, which is most comfortable, regardless of different technological features. Their findings were based on the injury rates being decreased significantly by those who selected inserts (which varied widely in component materials) based solely on comfort, versus those who wore no inserts [9].

Malisoux and colleagues studied the affects of switching to different types of running shoes on injury rates and found that runners who frequently switched between different pairs of running shoes had a decreased risk of injury, compared to those runners who predominantly wore only a single pair of running shoes. Malisoux suggests that multiple shoe use may be protective against injury, by inducing a variation in external or internal forces, which may diminish effects of, overuse syndromes [10, 11].

Interestingly, Kluitenberg with Dutch researchers from the University of Groningen found that running-related injuries in 1696 novice runners followed over a 6-week training period were not significantly related to the age of the running shoes worn [12].

Thiesen reported another randomized study—247 runners—from the Public Research Centre for Health in Luxembourg found a similar injury risk between one group wearing shoes with a hard midsole, verses a second group wearing a soft midsole over a 5-month period [13].

Summary

Sports medicine professionals who are knowledgeable and comfortable in recommending appropriate athletic footwear and orthoses for their athletic patients will be providing the athlete with the greatest service. Health benefit claims advertised by shoe companies must be carefully scrutinized and supported by scientific research in order to protect patients from potential harm.

Having a solid game plan for recommending athletic footwear and orthoses for each athlete will be helpful in making critical decisions on athletic footwear. It is imperative for the sports professional to keep educated and to be aware of newer trends and technologies. The sports medicine practitioner must ultimately decide which shoes or which orthotic devices are most appropriate for each individual athlete.

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Part II

Running Footwear

Barefoot, Minimalist, Maximalist, and Performance

15

David W. Jenkins

Barefoot Running: The Background

Given the notion that our antecedents roamed the earth unshod or with the most minimal of coverings, it is farfetched to call barefoot running a contemporary activity. In fact, although the newfound excitement by recreational runners is recent, barefoot running is not new at all to old-timer or historically versed runners who are familiar with impressive world class efforts by barefoot runners in years past.

Similarly, prior to recreational running becoming mainstream, it was commonplace for coaches at most competitive levels to integrate some barefoot training in their workouts. Indeed, the author regularly engaged in structured barefoot sessions in high school track and cross-country in the late 1960s.

Websites and Robbins

In recent years there has been a significant interest in what is perceived as a "new" movement (some would call it a fad) called barefoot (BF) or unshod running. One of the prime movers of this movement were web sites devoted to not just barefoot running but to the unshod condition as an alternative lifestyle. These sites, most notably runningbarefoot.org which originated in 1997, began posting claims about BFR based on anecdotal evidence or extrapolation of research findings [2, 3]. Arguably, the study by Robbins and Hanna in 1987 that asserted "The solution to the problem of running-related injuries could be as simple as promoting barefoot activity" prominently touted on BFR proponents' websites could be considered a

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catalyst for not only the interest in BFR by would-be participants but the research community as well [4]. In more recent times, there are now web sites devoted to debunking claims made by BFR aficionados [5].

Born to Run

In 2009, the very popular book, *Born to Run: A Hidden Tribe, Superathletes, and the Greatest Race the World Has Never Seen*, by Christopher McDougall ignited significant interest in the concept that injury rates in runners have remained unchanged despite years of significant improvements in running shoes and that the reason runners get injured may be the shoes themselves. Driving this premise was his observation of the Tarahumara Indians of Mexico who customarily run ultra-marathon distances with simple coverings and apparently suffer none of the modern "running injuries" plaguing those in current society [6]. Fueled by *Born to Run* and a great deal of anecdotal claims in the popular media and on websites, many runners sought out this possible solution to alleviating or preventing running-related injuries or as a means to boost their performance [6–8]. The mere suggestion of performance enhancement and/or injury reduction makes understandable the onslaught of interest in BFR. Concurrently, there arose a number of claims, especially in online posts that were seemingly supported by research evidence. What was taking place, however, was that BFR proponents claimed some publications' findings, such as BF persons had better balance, reduced impact forces or stronger plantar intrinsic musculature to name a few, could be extrapolated to better performance and/or reduced or prevented injuries. This faulty logic, well intentioned as it may be did stimulate a tremendous degree of serious investigation by top biomechanists to confirm or refute existing publications on the topic or explore changes or differences associated with BFR versus shod.

Shoes Are the Problem Not the Solution

Additionally, *Born to Run* and BFR proponents' essays disagreed with clinicians and shoe companies that viewed feet as intrinsically fragile and thus could not sustain the rigors of running without protective cushioning. The doctrine put forth by BFR proponents is that feet are not inherently weak or in need of protection as well as the notion that centuries of more restraining, motion-inhibiting, and progressively more supportive shoe gear has induced an atrophy of the feet through disuse, and, in fact, an unshod condition is best for opportune biomechanical function. This thinking led to such notions that running barefoot could reverse such weaknesses as atrophied plantar intrinsic musculature with a resulting "a cure" of plantar fasciitis.

Another assertion posed in *Born to Run* and echoed by BFR aficionados was the dearth of running-associated afflictions in unshod cultures. Coupled with claims of an unchanging rate of running-related injuries despite years of research-driven improvements in shoe fabrication technology piqued further interest.

In essence, shoes are the enemy according to BFR enthusiasts. They remove neurosensory feedback, the raised heel leads to impaired balance, they overly cushion, they confine and deform. A study by Morio et al. lent some support to this premise when they reported that shoes restrict the natural motions of the feet and this "could play a role in possible injury mechanisms" [9].

This paradigm shift seems far removed from the dogma of running injury pioneers Brubaker and James. Their publications in the late 1970s were the definitive resource for running-related injury etiologies, treatment, and prevalence for their time and led to the statement by James et al. "It is our contention that if an adequately designed shoe were available, many of the problems attendant to long distance running, short of training errors, could be prevented [10, 11]."

Collisions in Nature

Arguably, what opened the floodgates to a serious look at BFR and its purported superiority was an article published by Lieberman et al. in the journal *Nature*. A summary of his conclusions includes:

(a) High impact collisions are associated with those that rear foot strike (RFS) and are thus averted by those running BF or minimally shod because of the natural tendency to alter their kinematics to a fore foot strike (FFS) pattern.
(b) Modern running shoes have not improved running-related injury rates, and the higher heel and increased cushioning encourages a RFS and higher impacts.
(c) Increased cushioning also reduces neurosensory feedback (proprioception) that would otherwise dictate a runner's foot strike pattern.
(d) Shoe construction, especially inherent stiffness and arch support/motion control modifications, may lead to weaker musculature, excessive pronation, and even plantar fasciitis.
(e) Quality prospective studies are needed to indeed see if those who have a RFS pattern experience a higher rate of injuries [12].

It was these findings and hopes for improved performance and reduced injuries that spawned the modern barefoot/minimalist running movement. Conversely, many clinicians have voiced concerns and skepticism as they observe many of their running patients hobble into their offices after giving this "new" technique a try.

Review of the Literature 2011

In 2011, the author and D. Cauthon published what was, up to that time, the most extensive review of the literature on BFR. The primary conclusions were as follows:

1. Despite numerous studies demonstrating notable alterations in kinematics while running BF versus shod, there was no evidence that these changes resulted in reduced injuries or improved performance in barefoot runners.

2. Some supporting evidence for increased strength of the plantar intrinsic musculature and a more efficient energy utilization was noted, but there was no evidence that these changes resulted in less injuries or improved performance.
3. Barefoot running by individuals with a lack of protective sensation, such as with diabetes, is hazardous and should be avoided.
4. Inclusion of BFR as a part of the overall training regimen may be of benefit to some runners.
5. Those instituting a barefoot training regimen should very cautiously build their time and mileage so as to maximize the time for adaptation.
6. Some runners with inherent biomechanical dysfunction and related injuries that have benefited from biomechanical intervention such as motion control shoes and/or orthotics should proceed with caution and only if professionally supervised.
7. At the time of the review, clinicians had concerns about BFR leading to injuries such as stress fractures and Achilles tendinopathy, but evidence at that time pro or con was nil.
8. Concerns about surface risk, hygiene, and general hazards were found to be unsubstantiated.
9. The overriding conclusion was that many of the purported claims **may** have had merit but evidence to that date did not support or refute the contention that BFR led to improved performance or reduced or prevented injuries. The recommendation was made for much more research on barefoot running to better answer those questions [1].

Abundant Studies

Although the above conclusions have changed very little in the last 5 years, the volume of investigatory studies and publications since then is massive.

What follows is an update that reviews the current state of the evidence: BFR and the minimalist movement. As with the original review, this chapter attempts to view claims both advantageous and disadvantageous and update the state of evidence. Although studies on minimalist footwear were nil in the 2011 review, it will be apparent that much new information on that topic exists. Although studies on a newer style of shoe, the maximalist are nonexistent, the purported advantages and disadvantages are discussed.

Advantages of Barefoot Running

A number of advantages have been attributed to running unshod or in minimalist foot wear. In earlier publications such as the author's in 2011, much of the "evidence" available at that time was anecdotal or based on logical extrapolations. The following sections will summarize the evidence to date of many of the purported benefits.

Kinematic Alterations to Runner's Gait

Though not necessarily an advantage, the following kinematic observations have been consistently documented by many investigators in unshod runners. They include:

1. Decreased stride length [13–16]
2. Increased cadence [14–17]
3. A more plantar flexed ankle position at *foot strike* [12, 15, 18, 19]
4. A more anteriorly placed location for foot strike [12, 15, 16].
5. Increased knee and hip flexion and greater knee flexion velocity at *foot strike* and less knee flexion during stance when barefoot [12, 15, 17, 18, 20–22].
6. An increased range of motion of the ankle during the absorptive stage of stance [17, 18].
7. An increased stiffness of the knee and ankle joint/leg [15, 23–25]
8. A lower contact and flight time [16, 17, 26]
9. Reduced vertical displacement [27, 28]
10. Hip external rotation and adduction are reduced in the BF condition [12, 15, 16, 22, 26, 29]
11. A greater deformation of the arch height during contact [22]
12. A greater inverted position of STJ at contact with overall reduced STJ motion and significantly lower rear foot eversion via a lower eversion moment in early stance during barefoot running compared with the shod condition [15, 30].
13. Reduced joint torques at the hip, knee, and ankle were observed with running shoes compared with running barefoot [26].

The kinematic findings noted above are essentially unchanged from the 2011 publication with numerous confirmations since. Some modifications in the variables and methodology have occurred and will be mentioned below.

Kinematic Changes ⟷ Impact Forces

In discussing the kinematic changes seen in BFR, it is difficult to separate kinematic changes from the reduction of impact forces discussed in the following section. The changes are the result of a natural tendency to avoid striking the heel once unshod (unprotected) due to the inherent discomfort. These changes are presumed responsible for the lessened impact forces in the BF runner.

Kinematic Changes and Mechanisms for Impact Attenuation

Leg Stiffness

One such change is leg stiffness. As overall leg stiffness plays a role in "shock absorption," it is not surprising that changes in leg stiffness occur when transitioning from shod to BF. An increased stiffness of the ankle appears to reduce the slap of heel to ground at contact [24]. Indeed, the overall increased stiffness of the leg during the stance phase was found in the barefoot condition and may be one of the ways a BF runner spontaneously adapts to reduce the impact [25].

Ankle/Knee Flexion

Similarly, the more flexed knee and ankle position at foot strike serves a shock absorption function. Although the knee is more flexed at contact in the BF condition, the actual total knee flexion that takes place during the rest of stance is reduced [22].

Coordinative Strategies

Kurz and Stergiou discussed the idea of coordinative strategies as responsible for the kinematic changes seen in the BF runner. In essence, the runner unconsciously alters their foot position prior to foot strike so as to maximize not just shock attenuation but overall gait efficiency. In effect, the perception of impact as well as sensory input determines the chosen positioning of lower extremity components. They describe an ankle that is held more plantarflexed and a subtalar joint that is more inverted which in turn will shift a greater degree of shock attenuation from the subtalar joint to the calf musculature as well as maximize a runners' performance [30].

Divert et al. evaluated EMG findings that may represent coordinative strategies. Besides confirming a reduced impact peak in BFR they also found higher preactivation of posterior calf musculature in BFR versus shod and reiterate Kurz and Stergiou claim that this process is what readies the locomotor system for an *expected* impact with the ground—in this case to reduce or eliminate a heel strike [16].

Increased variability

One of the observations presumably related to the coordinative strategies in those running BF or with a forefoot strike pattern (FFS) is an increased variability in the observed gait [31, 32]. As will be discussed in later sections, this variability may be due to better ground surface feedback seen in the BF condition and is one means to reduce impact forces as the variability reflects the ongoing alterations necessary for this purpose [30].

An example of this variability may be the finding that running BF on hard surfaces does not result in greater ground reactive forces as the surface feedback seems to adjust the leg stiffness and thus the overall shock absorptive status (Fig. 15.1) [33].

Foot Strike Pattern

Rear Foot or Forefoot Strike: Demographics

In the initial wave of interest in BFR/Minimalist, the dogma, especially in the lay public was that those wearing shoes were rear foot strikers (RFS) and those BFR/minimalist were forefoot strikers. A number of observations report this is not necessarily the case. Hatala et al. observed habitually BF subjects and found 72% of runners were found to be RFS [34]. Hasegawa et al. observed elite competitors participating in a half marathon and report 75% RFS, 23.7% midfoot strikers (MFS), and 1.4% FFS [35].

Fig. 15.1 Barefoot on pavement

A more recent look at the foot strike pattern in BFR provides a greater analysis of other variables taking place during gait such as running speed, distance, heel height (drop), training level, and running frequency rather than the use of cushioned running shoes [24, 34, 36]. Gruber et al. in 2012 determined that running surface hardness was a significant factor in foot strike pattern when it was shown that habitual shod RFS BFRs tended to RFS on softer surfaces and MFS/FFS on hard surfaces. This gives credence to the idea that the change to FFS while running BF is protective [37].

One of the themes of more recent studies is the query as to the above changes being the result of the footwear or lack thereof, the foot strike position or a combination of both [38]. As will be noted later, those believing it is not the BF condition but where the runner strikes on the foot will try and make the case for one not needing to be BF to garner the above changes. Giandolini et al. concluded in their study that a midfoot strike pattern was most effective intervention in reducing the loading rate [39].

Joint Torques

In an effort to investigate a more direct relationship between the observable changes in BFR versus shod and running injury etiology, some studies have evaluated torque forces in lower extremity joints. Kerrigan et al. describe significantly increased joint torques at the hip, knee, and ankle with running shoes compared with running barefoot. Torques appear to be due to heel elevation and medial support commonly seen in modern running shoes. How these findings may impact injuries will be discussed below [26].

In summary, although not necessarily an advantage or explanation for how BFR could lead to reduced injuries, there are significant changes that are indisputable in a comparative examination of a shod runner versus a barefoot runner. These modifications will, in part, be responsible for many of the touted advantages that are described below.

Reduction of Impact Forces

Shoes and Impact Forces

In the earlier nonacademic dogma, it was claimed shoes really were not effective in reducing impact forces. In fact, Robbins and Gouw complained of the "false sense of security" they believed shoe companies promoted with a combination of increased cushioning, comfort, and slick marketing. Runners are left with no sensory incentive to modify their foot strike [40].

Lieberman adds that those that utilize a FFS do not require shoe cushioning as they do not sustain an impact peak [41].

Fong et al. performed a systematic review that compared shod to BF as per impact attenuation and found insufficient evidence that demonstrates the ability of cushioned shoes to reduce vertical ground reaction force or loading rate during walking or running [42]. Fong claims that loading rate and tibial acceleration should be the key parameters utilized in future research because of their association with running-related injuries.

Impact Forces and Injury

Many in the running community claim most of the blame for injuries related to running is due to training errors and therefore may very well be unrelated to a runners' footwear or lack thereof [11, 43]. Nonetheless, many investigators generally concur that impact forces especially vertical loading rate (VLR) associated with running are substantial and may be a significant contributor to running-related injuries seen by clinicians [12, 20, 26, 34, 42, 44–49]. Of note, is that VLR is reportedly lower in shod FFS versus RFS running [18, 39, 50].

Absence of the Impact Transient

As noted earlier, much of the current interest in BFR came about as a result of the Lieberman et al. paper that introduced many to the vertical ground reaction force chart that pictured the impact differences between a rear foot striker and a forefoot striker—the definitive peak is absent in forefoot and midfoot strikers [12]. The impact peak is seen below in Fig. 15.2.

As noted above, it is hard to separate the kinematic changes with a BF pattern and reduced impact. Lieberman has cited the principle that most people land on the ball of the foot when they jump as the most basic example of the natural kinematic change resulting in reduced shock [41]. The following sections will look at specific kinematic findings and how the research interrelates them to impact reduction.

Decreased Stride Length/Increased Cadence

One of the kinematic changes seen with BFR is a reduced stride length. A number of investigators have shown that impact forces are less as the stride length is shortened. This finding will become significant in the discussion of injuries later [27, 51–55].

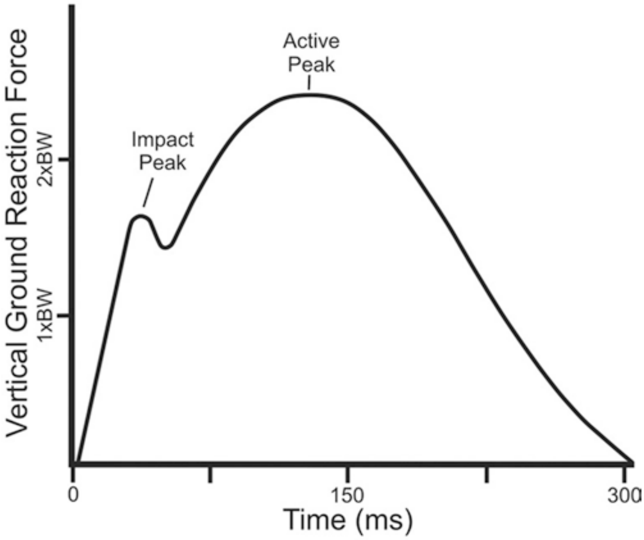

Fig. 15.2 Ground reactive force graph

Plantarflexed Position of Ankle at Foot Strike: Forces Redirected
An anteriorly placed foot strike results in a more plantarflexed ankle and therefore will result in greater forces imparted to the posterior leg musculature [24, 56]. Although a significant mechanism for shock attenuation, the impact forces therefore do not vanish but are manifested differently. The implications of this force conversion as it relates to injuries will be discussed later.

Knee and Hip Position and Motion
For improved shock absorption, the hip and knee are more flexed on impact but likewise partake in the overall greater leg stiffness while running unshod with a decreased range of motion [12, 17, 22].

Balance of Forces over Foot
As recently as 2015, Cooper et al. confirmed that most barefoot runners adopt a FFS with reduced forces and a more balanced force distribution across the plantar surface [57].

Greater Arch Deformation and Shock Attenuation
Perl et al. discuss below the economic benefits of an arch allowed to deform, which it does to a greater extent in the BF condition. This finding may also contribute to better shock absorption [22].

Increased Economy of Running

Some of the earliest studies on the possible benefits of BFR focused on one of the most obvious characteristics of being unshod, the absence of shoe mass and how this reduces energy utilization and improves running economy [58, 59]. Since that time, many more studies have taken place that evaluate this parameter.

Improved Economy: Shoe Mass, Kinematic Effects, or Both?

Most investigators assessing the changes in BFR early on believed removal of a shoe that a runner must repeatedly accelerate and decelerate over the course of a run is what led to a more efficient use of energy in a BF condition. Others believe an economy boost is appreciated irrespective of shoe mass effect.

Shoe Mass Only

Reeves et al. looked at running economy at varied intensities and found significant reductions in energy use while shod but attribute it to the reduction in mass in the BF condition [60].

Altered Kinematics May Result in Improved Economy

Divert et al., in describing impact reduction via preactivation of the triceps surae, suggest that those changes seen in a BF condition such as a FFS reduced contact time, and muscle length changes could manifest improved storage and restitution of elastic energy via augmentation of the stretch-shortening cycle behavior. Although concluding the mass of shoe was responsible for an increased oxygen consumption in shod running, they and Squadrone and Gallozzi believed shoes also caused a dampening of this energy storage and restitution, thereby adding to the reduced efficiency in the shod condition [16, 29, 61].

Nigg notes that besides the mass of the shoe that must be accelerated and decelerated, it takes work to deform and rotate the shoe sole and energy is lost to the midsole and metatarsal-phalangeal joint [62]. Besides a loss of energy through dampening, Webb et al. considered the energy required to repeatedly deform a shoe during a run reduced efficiency [63].

What a number of investigators are now looking at is an apparent improved energy use and efficiency after correcting for the mass of shoes and how this may be taking place. Specifically, they are considering if the profound kinematic changes noted in the BF condition directly improve energy utilization, thereby defining the BF condition more efficient [22, 64].

Unleash the Natural Shock Absorption as a Means to Increase Economy

Perl et al. observed that those running in minimalist shoes appear to have a greater deformation of the arch height during contact which they surmise may unleash the elastic energy storage and recoil capacity of the windlass mechanism of the arch [22]. The FFS pattern allowed a recovery of the elastic energy of the Achilles and plantar arch which would not be possible with a RFS. This study controlled for shoe mass by adding weight to the BF subjects' feet and also controlled cadence. The improved economy was present regardless of foot strike style. Their study also reported on the finding of reduced knee joint flexion in those running barefoot or in minimalist shoe gear. That knee flexion and adduction as well as external rotation of the hip are reduced in the BF condition had been reported previously [12, 15, 26, 29, 61]. This reduced knee flexion could be another reason BFR/minimalist running is more energy efficient. The lower flexion of the knees reduces the eccentric load on the quadriceps and keeps the Achilles tendon in a more ideal state of tautness. This study also lent some support to the idea that supportive shoes and/or arch supports/orthotics may inhibit the natural function of the arch with regard to energy production. In summary, the type of foot strike, FF or RF did not seem to be as important in improving energy economy as did the nature of shoe gear did [22].

Familiarity with BFR Technique: A Factor in Energy Efficiency

Vincent et al. tried to standardize the subjects with regard to experience and foot strike pattern and found no difference in energy use between shod and BF conditions. They attribute this to the experienced status of subjects as they inherently modulate their kinematics to standardize energy use without regard to being shod or BF [28].

Warne and Warrington evaluated running economy via oxygen uptake in runners wearing minimalist footwear; Vibram Five Fingers (V5F) but not familiar with BFR and put them on a 4 week familiarization program and noted a near 9% improvement in running economy after the familiarization program. Interestingly, there was no significant difference in running economy at the outset between shod and unshod. After familiarization, BF was 6.9% more economical than shod [65].

No Economic Benefit

Franz et al. reported that there was no significant difference in running economy as per energy utilization between shod and BFR. Indeed the reduced weight was found to impact energy use but this downside seemed negated when running in lightweight minimalist shoes. In fact they found a slight advantage to being shod that may reflect an increased VO_2 due to higher cadence when BF [64].

Systemic Review of Economy Effects of BFR/Minimalist

Fuller et al. performed a systematic review and determined that although BF and minimalist shoes had a measurable effect on running economy compared to traditional running shoes, there was not a significant difference between BF and minimalist. In fact, they determined that only when the footwear is greater than 440 g, does the additional weight become a hindrance to running economy. Interestingly, traditional running shoes with characteristics of increased longitudinal stiffness, cushioning, and reported comfort had improved economy as well. They found no studies that assessed performance as it relates to shoe gear [66].

Cheung and Ngai performed a systematic review and meta-analysis on the effects of footwear on economy and concluded that barefoot running or running in minimalist footwear is potentially more economic compared to running in traditional running shoes. They present the caveat that many of the subjects were experienced in BFR and thus, those new to BFR or in transition, may not experience these benefits. The idea that reduced oxygen cost may improve performance is speculative [67].

It appears the debate as to the metabolic benefit of BFR is far from over. Kram and Franz take to task findings reported by Hanson et al. and point out only two out of seven studies found a statistical difference in oxygen consumption between BF and shod [61, 68]. Their concerns about systematic errors in methodology are at the root of disagreement [64, 69, 70].

Increased Proprioceptive Ability/Balance

Some of the earliest studies that evaluated the BF condition and led to the initial hype involved proprioception and balance. These studies assessed the performance of BF subjects, but in static circumstances. Findings stated subjects had better proprioceptive ability while BF as the shoe was said to create a barrier between the ground and plantar mechanoreceptors. These conclusions led to the extrapolation that, therefore, those running BF must likewise have better sensory input/proprioception and thus better performance and reduced injuries. In effect, besides better balance, the runner would be better able to make the kinesthetic adjustments to reduce impact via improved neurosensory feedback [4, 71–74]. Squadrone et al. found that even a minimalist shoe provided improved static and dynamic ankle position sense over that of a conventional running shoe noting that cushioning in shoes impairs the position awareness [75].

Sensory Feedback Interrelated to Kinematics

Fleming et al. in their study that demonstrated an immediate ability of habitually shod runners to convert to a BF style speculate that this is accomplished in part to the "acute awareness of altered impact forces by tactile receptors in the foot and proprioceptive organs in the shank" [17].

Ferris et al. observed the changes in leg stiffness as their BF subjects ran on surfaces of varied hardness. They point out the impressive ability of a runner maintaining the center of mass while traveling over an ever-changing surface as it pertains to hardness. They explain that this capacity is the result of an instantaneous ability to adjust leg stiffness. The authors admit that the neurological mechanism for how this takes place is unknown but suspect that the mechanism must include plantar sensory feedback that would most assuredly be greater unshod [33]. Along this thinking, Kurz et al. who described the so-called coordinative strategies evoked by BF running (see above) also noted BF runners' gait manifested a much higher variability. That is, compared to a shod individual, the foot is in a continual state of adjusting to the running surface. They believe this variability is the result of a vastly improved sensory feedback/proprioceptive state whereby mechanoreceptor feedback modify joint kinematics in the favor of reducing impact forces a process that may be hindered by wearing shoes [31].

Improved Balance Barefoot?

Several more recent works appear to confirm the idea that those barefoot enjoy improved proprioception and balance [75, 76]. It seems this improved balance has only been observed in either static studies or in the case of Rose et al., (dynamic) during the performance of a single leg jump landing. The improved balance was said to be the result of a reduced filtering of sensory feedback while in the BF condition [77].

Another downside of traditional running shoes is the associated typical heel height of 10–12 mm the so-called drop. There is evidence that a higher heel height can impede balance. But those studies evaluated a heel height significantly higher than the typical drop in a running shoe [77–79].

Better Balance with Shoes

Horgan et al. and Koepsell et al. report that contrary to many prior studies, they found that, at least in elderly population that wearing shoes provided better balance and reduced fall risk than did going BF [80, 81].

As part of the debate it is only fair to note some propose an unprotected foot (BF) may subject the pedal mechanoreceptors to greater direct impacts and damage thus reducing their neurosensory feedback [82]. While others suspect mechanoreceptors plantarly may play a less significant role in proprioception that such things as muscle spindle afferents, golgi tendon organs and visual clues [83–85].

Increased Strength of the Musculature and Arch Structure

Shoe-Related Disuse

A number of BFR proponents have proposed that shoe gear, especially today's running shoes, are stiff, confining and overly supportive and cushioned. The result is a foot that becomes weak and dependent. The planter intrinsic musculature atrophies and puts the shod person at risk for arch collapse and even such maladies as plantar fasciitis. One running BF would thus develop stronger plantar intrinsics and even overcome plantar fasciitis. Of the major claims about BFR discussed in this paper, changes as they relate to the plantar musculature and arch structure appear to be the least investigated.

Kinematics Change and Arch Utilization

Considering the alteration from a RFS to a more forwardly placed one, it would make sense that the arch and thus the plantar intrinsics would be more greatly utilized and become stronger with a resulting higher arch that is better at shock absorption. Indeed, this is what was suggested by Robbins and Hanna in 1987 [4].

Plantar Musculature Can Be Strengthened

Plantar musculature can be strengthened and for some athletic activities this can be an augmenting factor. Goldmann et al. concluded that toe flexor musculature was strengthened via training, and although this did not assist with basic running or walking, it did so with such activities as sprint starts, horizontal jumping, and side cutting. Although they did not look at BFR, they opined that BFR may indeed provide a similar training effect and boost performance [86].

Bruggemann et al. believed plantar intrinsic muscle strength was compromised by stiff-soled shoes with arch supports and in a project funded by Nike did find better developed and stronger plantar intrinsics in participants using Nike Free footwear during warm-ups. As may be expected, concerns regarding methodology and bias surround this report [87].

Intrinsics Recruited While Barefoot

Although not necessarily related to better performance or reducing injuries, the finding that those BF demonstrate a higher recruitment of the plantar intrinsics for balance suggests a possible advantage of the BF condition [88].

Compared to other of the claims, studies evaluating the strengthening benefits of BFR are nil. Despite some evidence that BFR/minimalist strengthens plantar foot musculature, no studies have yet associated those changes to improved performance or reduced injuries.

Reduction in Running-Related Injuries

Injury Reduction Key Motivation to BFR

It goes without saying that to serious runners, preventing and reducing injuries is paramount. It is not surprising, therefore, that the premise BFR could prevent or reduce running-related injuries is the primary motivating factor runners report for why they would consider trying BFR. Likewise, the chief reason those queried would not try BFR is an apprehension that BFR would lead to an injury [89]!

Injury Rate Unchanged Despite Changes in Shoe Gear

In an attempt to consolidate prior studies on prevalence of running injuries, van Gent et al. completed a systematic review in which they reported the rate of running-related injuries to be between 19 and 79% within a given year [90].

Some investigators conclude that yes, the rate of injury has not seemed to improve through the years but if you factor in the demographics of who is now running currently versus the runners of the 1970s, the fact that injuries have not soared is remarkable given the far greater numbers and comparatively less conditioned runners of today [91]. Indeed, maybe the significant changes in shoe gear have been of benefit?

Running Shoe Design and Dogma

Despite the continued injury rates, proponents of modern running shoe design claim that cushioning and motion control features are required in order to protect runners from injury. Dogmatically, clinicians continue to prescribe more cushioned and controlling shoe gear even though there is no evidence to support the effectiveness of high quality running shoes in preventing injury and may indeed have the potential to cause harm [92]. In fact, Clinghan et al. concluded that expensive running shoes were no better at reducing impact forces than low cost shoes were [71]. Another aspect of the traditional running shoe, the increased heel height, is thought to encourage a RFS and thus increased impact forces. Without the extra heel height, might a runner instead utilize a MFS/FFS [20]?

Along similar lines, Richards et al. did an extensive review on the available literature and concluded there have been no studies that assessed the advantages (injury rates, performance or global health and well-being) of prescribing running shoes that incorporate a design of heel cushioning, elevation, and pronation control. Indeed in their conclusion they consider the possibility that the current design can cause harm to runners [92].

More recently Knapik et al. compiled extensive prospective studies of military recruits in which attempts to match a type of running shoe to a given foot type (plantar shape) had no effect on the rate of injury during boot camp activities, therefore calling to question the dogma of providing a neutral shoe to a high arch foot, a motion control shoe to a flat foot and so on [93].

Reduced Injuries and Better Performance Extrapolated from Research Findings

As noted earlier, proponents of BFR deduced through logical assumptions that kinematic and other changes seen with BFR could pan out as a means to prevent or limit running-related maladies. It would seem that documented improved lateral stability seen in the BF condition would lessen ankle sprains in that group. Surely reducing impact forces could lessen the prevalence of conditions thought due to high impact forces seen with running. Stronger plantar musculature would lead to a cure for plantar fasciitis!

Genesis of Shoes and Injury

Well before McDougall's *Born to Run* and Lieberman et al.'s *Foot Strike Patterns and Collision Forces in Habitually Barefoot Versus Shod Runners*, Robbins and Hanna were the first to associate a lower rate of injury with a BF condition. Their article's conclusion "The solution to the problem of running-related injuries could be as simple as promoting barefoot activity" was a major catalyst in the association of one's shoe gear status or lack thereof in running-related injuries [4].

Five years ago the authors' review found that most studies focused on the observable changes seen in the BF condition [1]. More recently, there appears to be more of a focus on connecting those changes with possible alterations in genesis of, prevention of, or treatment of injuries. Another direction that research has taken is can these changes and their potential benefits be appreciated by incorporating BF kinematics but while remaining shod.

Barefoot Running and Injury Rate

It goes without saying that definitive studies associating the BF condition and injury rates be undertaken. Altman and Davis completed a prospective review of 201 runners and found the BF subjects experienced fewer overall musculoskeletal injuries but had similar injury rate to their shod counterparts. Although BF runners had a greater number of injuries to the plantar surface and calf, they had fewer involving the knee, hip, and plantar fascia [94].

Running Injury Conditions

The following sections will look at specific conditions (some unrelated to running) and related studies and how observed changes seen with BFR might be utilized to prevent or manage injuries.

Chronic Exertional Compartment Syndrome (CECS)

Although a more defined discussion of running shod but with a "barefoot style" is presented later, a study by Diebal et al. that directly associates a BFR gait modification to an injury is discussed here. They report that runners diagnosed with chronic exertional compartment syndrome (CECS) enrolled in a running program utilizing a forefoot strike significantly reduced the presenting symptoms of pain as well as the measureable pressures themselves. In this instance the authors themselves are unclear as to how a FFS causes these changes but the measureable reduction in compartment pressures and lower eccentric stress on anterior compartment seen with FFS are suggested etiologies [50].

Osteoarthritis of the Knee Joint

To set the stage for many studies described below, Braunstein et al. report significantly greater mechanical stress (as reflected by the gear ratio) placed on the knee joint while wearing shoes compared to BF [95].

Kerrigan et al. reported that wearing running shoes led to an increased torque across the knee with resultant increased pressures at anatomical locales commonly at risk for knee osteoarthritis, the medial and patellofemoral compartments. Still suggestive of a correlation only, the findings are encouraging [26].

Shakoor and Block observed gait changes as they affect the knee joint afflicted with medial joint osteoarthritis (OA) and found that ambulating barefoot resulted in reduced peak loads in the knees (and hips) as well as a near 12% lower knee adduction moment [96].

Radzimski et al. completed a systematic review on the effects of varied shoe gear conditions on the external knee adduction moment (EKAM), a high degree of which has been associated with such pathology as medial knee compartment osteoarthritis. The evidence supports the notion that the EKAM is lessened in the BF condition with the proposed mechanism being the heel elevation in traditional shoes. A recommendation is made for developing shoe gear that can mimic the BF condition [97].

It would be presumptuous to associate DJD or other maladies of the hip and knee with wearing shoes but studies like this are seriously evaluating this connection. As a result, some investigators suggest modifications in shoe gear as a means to treatment and or prevention on OA in the hips and knees [26, 96].

Patellofemoral Joint Syndrome (PFJS)

PFJS and Impact Forces

Available literature associates an increased impact peak and increased eccentric load on the knee with the prevalence of PFJS [26, 98]. Given the observed changes regarding a reduced impact peak with BFR, a number of investigators have surmised BFR may be a preventative or therapeutic solution to PFJS in runners.

Bonacci et al. report a 12% reduction in peak patellofemoral joint stress in those subjects unshod versus a shod group and suggest running barefoot may prevent or treat patellofemoral joint syndrome. The reduced ground reaction force was attributed to the decreased stride length that resulted in a smaller knee flexion angle and extension moment [98]. Likewise, Lenhart et al. reported a 10.4% reduction of mean contact pressures of the patellofemoral joint simply by increasing the cadence by 10% in runner subjects. This change likewise reduced the overall contact area by 7.4% [54]. Of course this modification need not require a BF condition but lends evidence to the premise BF running may be of value to PFJS.

Sinclair likewise noted a significant reduction in the patellofemoral contact force and loading rate in the BF condition when compared to minimalist and traditionally shod conditions [99].

Kumala et al. compared forefoot strikers to rear foot strikers and similarly found that RF strikers had a significant increase in the patellofemoral contact force and stress. They venture a FFS pattern may reduce the risk of running-related knee injuries [100].

PFJS and Hip Mechanics

Noehren et al. note many studies that have found PFJS is more commonly seen in runners who are found to have an increased hip adduction a well as a greater peak hip rotation, two characteristics found to be reduced in a BFR pattern [101].

Iliotibial Band Friction Syndrome

Some anecdotal reports and a number of risk factors that have been associated with ITBFS that are said to be reduced in the BF condition lend to notion that BFR may be helpful for this condition. Noehren et al. and McCarthy et al. describe the association of ITBFS and PFJS with an increased adduction and internal rotation of the hip. After determining that BF running led to a significant reduction in the degree of these parameters, it could be concluded that BF running may play a role in preventing or treating ITBFS [102, 103].

Stress Fractures

Of the injuries affecting runners, one of the most attributable to vertical impact peaks and loading rates during initial contact are tibial stress fractures [45, 47]. Therefore, lessening these forces has been a major topic of investigation.

Zadpoor et al. performed a systematic review on the association of lower extremity stress fractures (the majority, tibial stress fractures) and ground reaction force. They discovered no correlation with the amount of GRF and development of a stress fracture but did find a significant association with stress fractures and the vertical loading rate of GRF [49]. This is relevant as the major distinction regarding impact forces between RFS and FFS is that although GRF may be similar the VLR is significantly reduced with a FFS [12].

Although a number of studies and reports discussed later will document clinicians and researcher's concern with BFR as an etiology of stress fractures, Edwards et al. found that runners could significantly reduce their probability of sustaining a tibial stress fracture by simply shortening their stride length 10% which in effect, reduces the strain magnitude, a variable they believe is more contributory to bone fatigue and damage than is the number of loading cycles. Given BFR has an associated shortened stride length, one could hypothesize BFR may have a preventative benefit for tibial stress fractures as could techniques such as utilization of a BF style while shod that encourage a shortened stride length [52].

Hobara et al. also associate high loads with tibial stress fractures and suggest that increasing cadence may reduce the prevalence of developing a tibial stress fracture. They pose the caveat that as one increases the cadence the increased steps result in a higher loading cycle with a resulting muscle fatigue which could in turn increase the chance for a stress fracture [53].

Plantar Fasciitis

Early on, proponents of BFR believed participation would strengthen the plantar intrinsics and therefore prevent and/or cure plantar fasciitis [4]. No evidence to this effect has been found but interestingly, BFR may have a beneficial effect on plantar fasciitis but for a different reason. Bowser et al. determined in a prospective study a strong correlation between those runners with high vertical loading rate, impact peak, and peak positive acceleration of the tibia and a predisposition to plantar fasciitis [44]. Pohl et al. also found an association of greater vertical ground reaction force load rate and subjects with a history of plantar fasciitis [48]. If indeed, BFR results in a reduced vertical loading rate, impact peak, and peak positive acceleration, then it could be deduced that BFR could be a way to prevent or treat plantar fasciitis. At this time, studies that directly assess this are not available.

Likewise in their review, Tam et al. list four reported findings thought to cause/contribute to plantar fasciitis and how BFR has been shown to negate three of the four and thus "theoretically implicate" a reduced risk [91].

Disadvantages of Barefoot Running

During the early hype on BFR, the majority of information, especially from the nonclinical perspective, related to the potential benefits with the clinical perspective one of skepticism and concern over potential injuries. The so-called downsides of BFR are also discussed in the literature but not with the same fervor as linking the changes with BFR to possible advantages.

The following section will review studies that evaluate some of the purported drawbacks of BFR.

Stress Fracture Propensity

Shift of Impact Location to Forefoot

One of the most commonly related concerns among clinicians as it relates to BFR/minimalist is that the shift to a forefoot impact will result in a propensity to metatarsal stress fractures. It was noted earlier that Cooper et al. described a balanced force distribution across the plantar surface in most of their subjects running BF but raised a concern that this change may place metatarsals at a greater risk for injury [57].

Bergstra et al. evaluated plantar pressures encountered by experienced female runners both in traditional and minimalist shoes and found significantly greater forces in the plantar forefoot in those using minimalist shoe gear and reason a transition to minimalist shoes may put one at greater risk for metatarsal stress fractures [104].

Increased Bone Marrow Edema in Transition

At the most basic investigative level, Ridge et al. evaluated two groups of runners via MRI exam after a 10 week running program. One group ran in traditional shoes and the other in Vibram Five Fingers (V5F). Even with a gradual transition period, the V5F group demonstrated significantly more bone marrow edema [105].

BFR Leg Stiffness Increase: Joints Versus Bones

As noted above, Sinclair et al. reported increased stiffness in limb and knee in the BF and minimalist condition. In their discussion they suggest these findings may potentially reduce the risk of knee pathology (soft tissue injury) but suggest bone injury may be increased [25].

Major Issue May Be Transition Period/Adaptation

In their report of case studies describing runners that encountered metatarsal stress fractures, Giuliani et al. conclude that although the stress fractures appeared to be related to the use of minimalist shoe gear (V5F), the stress fractures resulted not from BFR/minimalist per se but from an inadequate as well as an inappropriate transition to a BFR style gait. Therefore, running either BF or in minimalist footwear but maintaining a RF strike style can be fraught with increased shock and possible injury [106].

Likewise, Cauthon et al. in describing stress fractures related to minimalist shoe gear concluded they were probably the result of an absence of an appropriate transition period [107].

Salzler et al. reported on nine stress fractures (eight metatarsal, one calcaneus) that they attributed to the utilization of minimalist shoe gear but included the transition/adaptation time their runners reported. Interestingly, half of the injured did no transition period and the rest took between 2 and 8 weeks to adapt. The conclusion here is that even completing the recommended transition period was not necessarily protective from stress injury and that even though the major impact seen with heel striking may be reduced, the impact has to go somewhere, in this case the metatarsals. They also considered the concept that there is an individuality as to the ability of runners to modify their vertical leg compliance (create a better shock absorber) and those who became injured had less change in this parameter during the transition [108].

Achilles Tendinopathy

Transfer of Forces

One of the significant gait modifications seen with barefoot running is a significantly more plantarflexed ankle joint at foot strike. Intuitively, a major concern of this change is that the resulting eccentric stress on the posterior calf musculature via a far greater dorsiflexory moment would presumably set the stage for Achilles tendinopathy [24].

Almonroeder et al. report that BF peak Tendo Achilles (TA) force takes place earlier in the stance phase and results in a 15% increase in the TA loading rate which they calculated to be an additional 48 body weights encountered over the course of a mile run. The implication being BFR technique may result in higher risk of Achilles tendinopathy [109].

Sinclair likewise noted a significant increase in the Achilles tendon force in the BF condition when being compared to minimalist and traditionally shod conditions [99].

Kumala et al. compared forefoot strikers to rear foot strikers and notes that FF strikers had an increase in the plantarflexory moment and Achilles tendon force and loading. They venture a FFS pattern may increase the risk of running-related Achilles tendon injuries [100].

Effects on the Triceps Surae

Rao et al. compared the maximal muscle forces in the triceps surae during BF, minimalist, and traditional shod conditions and found no difference but note that due to the greater ankle range of motion seen in BF condition creates a more biomechanically efficient use of the triceps surae as it relates to force-length dynamics [110].

Stresses on Achilles May Be Reduced with Foot Position

Interestingly, some researchers [13] consider that stress loading on the posterior calf musculature/TA as well as the metatarsal heads can be reduced with the BFR style if the ankle is not too PF at contact, i.e., more of a midfoot parallel to ground positioning.

Increased Achilles Tendon Load Shod?

Wearing et al. describe findings that determine tensile load on the TA while walking in shoes with a 10 mm drop versus BF and found peak acoustic velocity and hence, tensile load in the Achilles tendon was actually increased while shod, a finding totally in contrast to what they expected. This would seem to confuse the premise that the BF condition or a zero drop shoe increases the load on the TA not to mention the dogma of heel lift therapy for Achilles tendinopathy [111].

Injury from Running Surface, Debris, or Soil Contaminants

Intuitively, it would seem that one running BF would encounter increased loads and thus a higher rate of injury by running on surfaces such as the pavement on a sidewalk. Lack of studies for this idea suggests this is not the case. As noted in the section on impact attenuation and proprioception improvements seen with BFR, it seems a hard surface encountered by the runner will institute mechanical changes resulting in changes in overall leg stiffness and foot position [33]. These automatic adjustments to surface impact are why Robbins and Gouw noted the human foot does not require any additional cushioning to manage the impact of running (Fig. 15.3) [112].

Although no studies have assessed the risk or related injuries to BF runners [113], surface hazards such as insects, glass, rocks, and thorns are said to be risks that are overstated and as simple to deal with as taking care as to where you place your feet [2].

Reports that plantar cutaneous tissue is especially resistant to injury and can tolerate markedly higher abrading loads than non-plantar skin may do little to allay the fears of a puncture wound [114, 115].

Runners That Require Mechanical Control for Existing Conditions

It makes no clinical sense that an existing patient successfully treated for a running-related injury that was found to be the result of a biomechanical dysfunction suddenly toss away their orthotics or motion control shoes and take up BF or minimalist running. But these patients may be hearing from friends or other nonclinical sources that all their running-related problems will magically disappear if they run BF. Foot care specialists may be called upon to advise these patient/runners and thus far, the prudent thing to do in these cases is stay the course with therapeutic biomechanical care. Despite the enormous amount of research taking place regarding BFR and injuries, no studies currently support BFR as a preventative/treatment intervention for a given running-related problem.

Diabetics and Others with Loss of Protective Sensation

Indeed, the risk of ulceration and injury for persons with diabetes is greatly increased in those that go barefoot [116]. Given the potential, it would seem quite inappropriate for one with lack of protective sensation to participate in BFR.

Fig. 15.3 Barefoot in the desert

Shoes That Mimic Barefoot Running (Minimalist Shoes)

In response to the hype regarding BFR and its possible benefits, there has also been a major effort by most shoe companies to develop and market minimalist (barefoot simulating) shoes. What follows will be an attempt to look at the most current evidence that relates to minimalist footwear with special attention to comparing it to the BF or traditionally shod condition. Do these shoes actually recreate the kinematics seen with BFR but also provide some physical protection of the foot true BFR does not? What aspects of a minimalist shoe are most desirable to best simulate the BF condition?

History

As convinced as one might be on the merits of a BF style promoted by aficionados' web sites and by reputable researchers from Harvard, many would-be BF runners had reservations with a truly BF status. Feet coddled and protected over lifetime were just not ready for the rocks and pebbles, temperature extremes and the weeks of "toughening up" and adaptation the true believers claimed was required. Even the Taraumara Indians in the Copper Canyons of Mexico whom Christopher McDougall wrote about in *Born to Run* used protective albeit, minimal foot coverings.

Nike, based on reports that elite track runners at Stanford University, incorporated BFR into their overall training program with the blessings of their coach who commented that BFR made them faster and less prone to injury, decided to develop a shoe that could simulate BFR [117]. The goal was to create a shoe that had no arch support, a very flexible structure, reduced or absent cushioning and reduced heel height. In 2004, the Free 5.0 was purported to have 50% the support/stability of a traditional running shoe. A tweak was made to the Free 5.0 creating an even less stable version as well as one more stable, the Free 3.0 and 7.0, respectively.

Enter Vibram FiveFingers (V5F) in 2006. Time Magazine's invention of the year in 2007 was essentially a "fingered" wet suit bootie with a Vibram sole that allowed runners to incorporate a BF style but still enjoy a degree of protection from the elements. V5F and numerous other minimalist shoes enjoyed remarkable success with huge increases in sales revenue only to have dramatic reductions in interest and sales in the last couple of years [108, 118]. Despite this waning demand for minimalist foot wear, there continues large volume of studies coming out re: minimalist shoe wear.

What Is a Minimalist Shoe?

Currently, nearly every shoe manufacturer has/or had their own version of a minimalist shoe. Among the models is a wide variety of degree of cushioning and heel elevation (drop). But the general common denominator is a lightweight shoe with a lower or nonexistent heel and reduced cushioning. Arch support, a rigid counter and stability enhancing and motion control features are absent and frowned upon. Calling minimalist shoes "barefoot shoes" is a misnomer at best and as Nigg points out is more of a marketing strategy [62].

Simulation of Kinesthetic Changes to BFR: Minimalist Running Is Not the Same as BFR

A number of researchers were quick to note that runners utilizing V5F appeared to appreciate the same kinematic benefits that BF runners did such as reducing the amplitude of the impact peak vertical force, increased cadence, increased leg stiffness, shorter stride, reduced contact time, encouraging a more forwardly placed point of foot strike, and a more greatly plantarflexed foot position. Even an improved toe push off was seen with V5F versus BF thought to be due to the added material protection [25, 29, 117, 119].

A number of investigators have attempted to evaluate how closely minimalist footwear simulates the BF condition. Hollander et al. compared BF with uncushioned minimalist shoes, cushioned minimalist shoes, and standard running shoes. What was discovered is that adding cushioning to the minimalist footwear reduced the similarity with the BF condition. Indeed the uncushioned minimalist shoes were the most similar to the BF condition. The reportedly primary finding of their study was that minimalist shoes vary in their ability to simulate barefoot running and when their findings are combined with some other studies, it seems absence of cushioning and a zero drop in a given minimalist shoe is what creates the most similar kinematics to the BF condition "Running in a minimalist and lightweight shoe is not the same as running barefoot" [14, 19]. Squadrone reported that those with lowest heels and least amount of cushioning in the heel region were most apt to encourage a RFS runner to convert and utilize a FFS technique and thus garner the purported advantages of a BF condition [120].

Additionally, Larson et al. reported that subjects wearing minimalist footwear are more likely to run with a RFS than those who are barefoot [121]. Lieberman concluded that because minimally shod runners have such a greater propensity to RFS than do BF runners, sensory feedback must play a major role in foot strike pattern [32].

Energy Utilization

The general consensus as per systematic review and meta-analysis on energy utilization is that minimalist shoes and BF condition garnered small improvements in running economy versus traditional running shoes [66].

Use as a Transition Tool for BFR

Besides looking at minimalist shoes at face value, there has been an effort to evaluate them from the perspective of, could they be a transition tool for those wanting to participate in BFR? This premise, intuitive on its surface seemed reasonable when Smith et al. compared V5F to BF and traditional shod conditions. They found that V5F indeed provided better stability (as per static balance measures) than BF but not as good as shod, therefore suggesting V5F could function as a bridge from shod to BF activity [122].

False Sense of Security

Some have considered the minimal protection afforded by a minimalist shoe to actually be a detriment in that it provides a false sense of security to those wearing it. Rather than the pure sensory feedback with BFR, the runner may not be as likely to heed the "warnings" of increased GRF and thus fail to alter the kinematics needed to navigate in the unprotected state. Goss et al. found that a group of subjects wearing minimalist shoe gear inaccurately reported their foot strike pattern. Thinking they were FFS, over 40% were actually RFS and given the lessened shoe gear protection, the authors opined, were putting themselves at greater risk for injury. As a result, they questioned if runners would fail to adopt a FFs strike pattern when using minimalist shoes [123].

Willy and Davis compared a cushioned minimalist shoe (Nike free 3.0) to a traditional running shoe and found that kinematic parameters associated with BFR were not seen with the cushioned minimalist shoe (same step rate, stride length) and in fact saw a greater impact loading presumably from the heel strike pattern taking place in a less cushioned shoe and thus feared that those utilizing minimalist shoes would be at a greater likelihood of injury in less protective footgear while not undertaking the typical changes seen with BFR that are known to reduce impact forces.

In other words, a cushioned minimalist shoe will give a runner a false sense of security with RFS and thus will actually increase the impact. Arguably it seems, the more minimalist the shoe, the more likely the runner will undertake a gait likened to the BF condition with the associated advantages. This agrees with Bonacci [14, 124, 125].

Along the same lines, a prospective study by Ryan et al. chronicled running injuries in subjects over a progressive 12 week regimen and found those in a "partial minimalist" (Nike free) shoe were significantly more likely to sustain an injury versus the standard neutral shoe or a true minimalist shoe (V5F). Further evidence for the "false sense of security" argument seems at hand [126].

Barefoot Required?

Some investigators have concluded it is not the state of being BF that is responsible for the purportedly beneficial effects but the changes to one's gait pattern that the BF condition seems to encourage. Therefore one should be able to still run in traditional running shoes and garner those benefits. Certainly one can endeavor to run with a higher cadence, shorter stride, and FFS pattern with shoes but the sense is that the impetus for the pattern is not genuine or is contrived. After all, the pure BF condition should naturally encourage this pattern.

"Barefoot Running" in Shoes

Thompson et al. investigated the specific effects of stride length in BF running. They found that BF running triggered the stride length reduction and associated GRF reductions, but because these potential injury reducing changes also occurred when shod if the subject shortened their stride, they concluded, one does not need to run barefoot to garner the advantages, just their shorten their stride [127].

RFS Versus FFS Shod

Along the same lines, Daoud et al. retrospectively found a significantly higher rate of injury in those (running shod) with a rear foot strike compared to those with a forefoot strike. So although this is not comparing shod to BF, it is hypothesized that the FFL with its associated reduced impact peak (as is seen with BFR) may contribute to the reduced injury rate (Fig. 15.4) [128].

Similarly, Williams et al. suggest that one need not wear minimalist footwear or run BF to manifest the purported benefits of BF running. They compared changes in kinematics between a shod runner with a RFS, a BF runner, and a shod runner that utilizes a FFS. Both shod with FFS and BF were found to have increased ankle plantarflexion, reduced absorbed power to the lower extremity at large but a power

Fig. 15.4 Barefoot versus shod

shift from the knee to the ankle. The study lends credence to the idea that one can make these changes simply by undertaking a FFS style in traditional running shoes but caution that the shift in power absorption seen at the ankle may simply be a trade-off resulting in an increase of injury risk distally on the foot and ankle [129].

Alternative Running Styles

In an effort to garner the purported benefits of a BFR style as noted above, several alternative running styles have arisen. Pose, Chi, and GFR to name a few. These have some variations but incorporate running with a midfoot/forefoot strike, shorter stride, higher cadence, etc. One can participate in shoes. A few studies look at Pose and like most on BFR, do demonstrate changes in gait but cannot associate the technique with improved performance or injury reduction.

Pose Method®

One alternative running style is Pose. Pose consists of a midfoot strike pattern with a flexed knee in stance. Proper positioning is brought about by a forward lean of the trunk and vertical alignment of the ipsilateral shoulder, hip, and heel of the supporting limb. One of the keys is the Pose Method is a utilization of gravity through falling forward and shifting supports by "dropping the feet directly under the body as you move forward" [130].

Arendse et al. performed an analysis on Pose running technique and found very similar kinematic changes to the BF condition including shorter stride length, smaller vertical oscillations and reduced power absorption and eccentric work at the knee joint. They make mention that their study did not look at the performance or clinical outcomes but the potential impact of this technique for these benefits [131].

CHI®

Chi running incorporates many of the same principals as Pose with proper posture, a midfoot strike, with a gravity assisted lean, but also incorporates spiritual aspects not unlike T'ai Chi such as relaxation, core engagement, and a mind-body connection [132].

Good Form Running® (GFR)

New Balance has introduced a program called Good Form Running or GFR based on the concept that many of the associated findings with BFR may be good for running performance and injury prevention. While not requiring a BF condition, it stresses a tall body alignment, midfoot strike, high cadence, and forward lean [133].

Risks of "Barefoot Running" in Shoes

Not all investigators were willing to claim a simple switch in pattern while still wearing conventional shoes was safe or effective. Boyer et al. were the first to look at shear loading rates as they compare with foot strike patterns. They, like prior investigators, found absence of vertical impact peaks with a FFS when assessing loading rates compared to shod condition but made the observation that shear forces (impact peaks in the posterior and medial directions) were actually higher with the shod FFS. They concluded that those who convert to a FFS while shod (as is common in Pose, Chi, and GFR) may not appreciate the protection from impact-related running injuries. They further elaborate that because VLR is reduced with a FFS, a switch to that pattern may be beneficial, especially if dealing with knee or anterior compartment (soft tissue) issues. However they found increased shear forces with FFS and made claim that because bones do not withstand shear forces as well, a move to a FFS may be fraught with osseous problems [38].

Implementing Barefoot Running

Are These Techniques for Everyone?

Some support the premise that we are designed to run in a way that is best suited to our structural and biomechanical design. Therefore, attempts to change or modify one's style with BFR and associated styles is unnatural and may lead to injury is one that some investigators are considering, especially when encountering many conflicting results [13, 123, 134].

Transition Period and Adaptation: Relationship to Injury

The importance of a gradual transition from conventional running shoes was appreciated even by Nike with its rollout of the Nike free [117]. Nearly every stakeholder in the BFR/minimalist running world seems to agree that IF one embarks on a BF/minimalist running program, an appropriate transition/adaptation period is imperative.

Injuries Related to BFR and Minimalist-Unrelated to Change in Pattern?

As previously noted, many of the investigators assessing the association of BFR to injury have opined that the activity itself is not necessarily the causative issue but the lack of adaptation or transition time is.

Inadequate Adaptation/Transition Period

One of the voiced concerns about BFR from clinicians discussed above was the propensity of stress fractures. Commenting on their stress fracture case studies, Giuliani et al. in associating stress fractures to minimalist shoe gear concludes that the causative factor was more likely an inadequate transition period [106].

Conversely, Salzler et al. also reported on stress fracture case studies related to minimalist footwear and found that those completing the transition period were not necessarily protected [108].

Despite the varied opinions, it would be safe to say that the consensus opinion is that for those considering and/or participating in BFR/minimalist to build up gradually; of course this is advice given to anyone beginning a new activity but seems especially dire with BFR [1].

Transition Is Period More Than Musculoskeletal/Cutaneous Adaptation

Could the current “blame” for injuries due to barefoot running be the result of an inability or failure to modify one’s foot strike? Is this part of the inadequate adaptation period that is frequently cited as the etiology for injury? In other words, in inappropriate transition period may be in part, a failure for the runner to change their gait pattern [23, 123]?

Failure to Change Kinematics While BF/Minimalist

Investigators have also shown concern for this premise. As noted above, Goss et al. found runners in minimalist shoes did not automatically switch to the BF pattern. They agreed with the false sense of security premise and warned of an injurious outcome for the runner attempting to use minimalist shoe gear for transition. This concept (that a large percentage of habitually shod individuals continue to heel strike when running barefoot and have an associated much increased impact peaks) is being researched as it may be one explanation as to why injury rates may not only be reduced in those running barefoot, but in fact be increased. The incentive for proper kinematics may be lost leading to greater not lesser impact forces [123].

This begs the question, do those that convert to BFR from longstanding time in shoes, need to "learn" those modifications mentioned earlier? Is the inability to transform or learn a factor in experiencing an injury?

Besides noting an inadequate transition period as an etiology for case study stress fractures seen above, Giuliani also considered running either BF or in minimalist footwear but maintaining a RF strike style could lead to possible injury [106].

Hazards of Incorporating Minimalist Footwear as Part of the Transition

Although Smith et al. believe minimalist footwear can function as a transition tool (a bridge) for implementing BFR, [122] some purists recommend that one does not bridge their transition to BFR with minimalist shoe gear as the tendency is that these shoes will give a false sense of security that a pure barefoot condition will not. The pure sensory feedback may be dampened that would normally limit the runners' impacts and mileage. A pure BF condition would be more apt to disallow a "too much, too soon, too fast" process.

Olin and Gutierrez evaluated parameters of tibial shock and medial gastrocnemius activation as they related to an *initial* transition from shod to barefoot. That is, a runner maintaining a strike pattern they utilized while shod—RFS. They concluded a much higher risk of injury during the acclimation period as both tibial shock and medial gastrocnemius activation were increased in the BF condition. Like many other investigators, their take home message emphasizes "the transition must be performed slowly, cautiously, and with knowledge about the proper toe-strike technique in order to avoid potential injury during the acclimation phase" [135].

Shih et al. came up with same conclusion as Olin as a result of their study of shod versus BF concluded that the defining issue with shock attenuation appeared to be the striking pattern and not the shoes or lack thereof. They express high caution for injury for those habitually shod that participate BF but maintain a heel strike pattern. Also as with Olin et al. they note the extra stress on the gastrocsoleus complex may be a factor for injury as well [136].

Some investigators believe this sensory feedback is crucial in the conversion to a FFL pattern. Altman et al. in their analysis of Lieberman et al. supplemental material, explain that the reason runners in V5F failed to fully take on a FS pattern associated with the BF condition may be that even the very minimal plantar material found with V5F may be enough to prevent proper neurosensory feedback to fully engage in BF kinematics and FFS pattern [13].

Inadequate Rest Periods

Hreljac mentioned above as to the association of impact forces and running injuries also believes proper rest periods and intensity are factors that are important irrespective of foot strike pattern [43].

Almonroeder et al. in their study on the increased forces encountered in the Achilles tendon with BFR noted above additionally conclude that BFR may require more rest between workouts and an especially gradual transition to BFR to counter this and so as to avoid the resulting tendon degradation [109].

Appropriate Adaptation/Transition Period

After all this discussion about how important the transition/adaptation period is, what exactly is that? Since BFR first came on the scene, a significant concern has been what would be an effective transition/adaptation protocol for conversion from a shod to BF condition? Initially, all runners had to go on were the BFR promotional web sites and early studies and commentary by Robbins et al. [2, 137].

These recommendations often suggest for new bare foot runners to listen to their body and go with the flow. Careful attention to the running surface is imperative. It goes without saying that besides the musculoskeletal adaptation, the cutaneous toughening is crucial. As far as designating a time frame, Robbins and Gouw in their early articles mention a range from three to six weeks [112, 114].

More recently, Rothschild recommends the transition period be no less than 4–8 weeks and presents probably the most complete preparatory program available. It includes core strengthening exercises, plantar sensitivity training, running form drills, lower extremity proprioceptive exercises, ankle flexibility exercises, plantar intrinsics strengthening exercises, and eccentric strengthening exercises via plyometrics [138].

Multiple authors have concluded the necessity of a gradual transition to BFR. But thus far there has not been a consensus for how long this transition should be [13, 57, 107, 113, 117, 123].

McCarthy et al., working on the premise that habitually shod runners could adopt barefoot kinematics via progressive minimalist running program and thus enjoy the purported advantages of BF running. They determined that indeed this was achievable and chose a 12 week transition period [139].

Davis et al. describe a protocol developed by Warden et al. utilized for return to sport following a stress fracture that is recommended for a BFR transition period [117, 140].

Gait Retraining

In light of the aforementioned benefits or downsides of BFR, one of the consistent themes in recent research is the idea of gait retraining to treat or prevent injuries. Investigators have suggested utilizing the associated kinematic changes seen with BFR/minimalist or BF simulated running. These findings can be used to actually treat not just running-related pathology but afflictions in the general population such as osteoarthritis of the knee.

Gait Retraining Methods for Conditions

Gait retraining, in general, is an emerging approach to a number of conditions and may or may not include any aspect of BFR or its simulated pattern. Noehren et al. describe a gait retraining protocol for treatment of patellofemoral joint syndrome that involved subjects altering their hip adduction angle as they observe themselves run (real-time feedback) [101]. Interestingly, as noted earlier, BFR was suggested as a treatment for PFJS though the mechanism was different [22, 26, 54, 98–100].

Crowell and Davis likewise employed gait retraining using real-time visual feedback of tibial acceleration to reduce the peak positive acceleration of the tibia, vertical force impact peak, and average and instantaneous vertical force loading rates and suggest their protocol may be a means to treat or prevent tibial stress fractures [45].

Samaan et al. evaluated 49 injured runners and instructed them on techniques for transition to BFR. Measured impact forces were noted to be reduced from these changes. They then make the claim that given impact loading has been associated with some running-related injuries, instruction and feedback on the proper forefoot strike pattern may help reduce the injury risk associated with transitioning to BF running [141].

Daoud et al. while concluding their cohort of collegiate distance runners was more apt to become injured if they were RFS also consider the value of converting RFS to FFS as a means to ward off or prevent injury. Likewise they raise the issue of would this transition help one variable (reduce impact) but create a new problem (Achilles pathology) [128]?

Achilles Tendinopathy Changes Gait

Azevedo found that runners with existing Achilles tendinopathy ran with reduced knee motion and reduced preactivation of the anterior tibial, gluteus medius, and rectus femoris muscles. Preactivation is crucial for shock absorption. Not determined was the issue of altered muscle function as a cause or as a result or both for Achilles tendinopathy. Although the premise of their study was to consider the role of muscle strengthening in Achilles tendinopathy, from the perspective of noted changes in preactivation as discussed above, could BFR have a positive effect with regard to Achilles tendinopathy [142]?

Maximalist Shoes

Hoka One One

Frenchmen Nicolas Mermoud and Jean-Luc Diard, both elite mountain runners, started Hoka One One 4 years ago. The heavily cushioned midsole, yet low weight, wide platform and a rocker configuration were said to best address the rigors of

Fig. 15.5 Hoka running downhill

mountain running—especially downhill where the gravity assisted pounding is greatest (Fig. 15.5) [143].

The line of shoes produced by Hoka One One incorporate several major variances from traditional running shoes. The most noticeable is a greater than doubling of the midsole volume but with an ethylene-vinyl acetate (EVA) roughly a 1/3 lighter than that typically used. This makes for a bulky but actually lighter shoe. The midsole is likewise fashioned into a rocker bottom configuration that purportedly guides one's gait along like a rocking chair which encourages a greater use of the gluteus musculature. A so-called active foot frame is designed to encourage the foot to sink deeply into the midsole and thus improve stability. The drop is in the range of 4–6 mm [144].

Anecdotal concerns include reduced proprioceptive ability due to the thick midsole, as well as the reduced mechanical efficiency related to the extra work of repetitively compressing the midsole and the functional impact of the rocker sole [145].

At this point in time, actual studies on maximalist shoes are not available. Davis and Ruder reported at the American College of Sports Medicine (ACSM) 62nd Annual Meeting that in comparing traditional shod individuals to those wearing maximalist shoes (Hoka Stinson), there was no difference in the vertical impact peak, instantaneous vertical impact loading rate, peak medial force, and peak vertical force. Average vertical loading rate was higher in maximalist and peak lateral force was lower in the maximalist shoe [146].

Last Word on Research

For those that compiled high quality systematic reviews on BF and Minimalist running, the general opinion was that the quality of studies with regard to methodological design was low. For example, they cite better standardization of subjects and running surfaces (treadmill versus overground running) as examples. The basis for many conclusions seemed weak and a call for better studies was paramount [20, 91]. As to specifics, Hall et al. recommend that future studies incorporate researcher blinding, randomization and that runner subjects better represent the running population. They also call for more prospective investigations into how injuries are impacted by BFR. In conclusion Hall et al. opine, "…no studies have directly investigated the effects of barefoot running on injury risk. Therefore, until this is addressed with empirical research, all links between barefoot running and injury prevention must remain hypothetical" [20].

Running Injuries and Causation: Shod Versus Unshod

As to the true causative factor in running injuries, a number of possibilities exist.

1. Due to shoe gear or lack thereof
2. Due to gait pattern, with or without shoes
3. Unrelated to shoes or gait pattern practiced but simple individual variation
4. Due to training errors including insufficient adaptation

Is there truth to adage that we are designed to run a given way that is most suited to our design and that attempts to change this with BFR and associated styles are fought with danger? That the defining factor is not shoes/cushioning/foot strike pattern, etc. but the individual morpho-mechanical make up.

As is often the case, the answer is probably a combination of factors and not any one. Indeed Zadpoor in assessing causation for stress fractures notes, "in explaining the results of the meta-analysis, one should note that in a group of people performing the same task, the ones who develop stress fracture should either have experienced more severe loading or have been more vulnerable to loading (or possibly a combination of both)" [49].

Although the last word on shoe gear is far from upon us, clinical wisdom and experience points to overuse/training errors as a far greater contributor to running-related injuries than shoes, gait pattern, or biomechanical dysfunction. This premise is not evidence based with little in the way of studies although James' pioneering study on running-related injuries did claim training errors as the primary etiology of running injuries (60%) [11].

Conclusions

1. As concluded in the author's publication in 2011, there still is not any evidence that BFR or minimalist footwear reduces injuries or improves performance.
2. Increased evidence that more directly associates some kinematic and mechanical changes seen with BFR/minimalist running with reductions of parameters known to contribute to injuries.
3. BFR/minimalist conditions may contribute to some injuries such as Achilles tendinopathy or stress fractures but it may be more the lack of an appropriate adaptation versus the actual style.

4. Some evidence that gait changes associated with BFR and minimalist may be therapeutic or preventative for some non-running-related pathology.
5. Performance enhancement may be the result of these styles but evidence is lacking. However, incorporating some of these techniques into the overall program of training continues to be generally accepted by many runners and coaches.
6. Evidence is lacking that portrays shoes as either preventing or causing injury.
7. The strong opinions of researchers that many injuries seen with BFR/Minimalist are lack of adaptation based lends support to the premise that running injuries are largely due to "too much-too soon-too fast" rather than shoes or gait pattern.
8. A major source of injury may also be individual variation. Some runners may be well suited to run BF and others not. Some may be injured trying to force a certain unnatural gait pattern for their inherent morphology and biomechanics.
9. Lack of consistency in methodology remains a notable barrier to obtaining best evidence. There remains a paucity of long term prospective studies that support the performance enhancing/injury preventing aspects of BFR/minimalist.
10. There seems a very large consensus that pro or con regarding BFR/minimalist participation, that the runner utilize a very gradual adaptation process.

It is apparent that BFR and minimalist excitement encouraged a tremendous amount of research. It is still far from clear where these studies discussed or those in the future will take us. Even as BFR and/or minimalist participation subsides, research efforts are sure to bring to light a number of findings that will help in the understanding, prevention, and treatment of not just running injuries but general afflictions as well.

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Triathlon and Duathlon

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Kirk Herring

Historically athletic competition is ripe with epic contests, performances, and events. We need look no further than our own backyard to find some of the most heroic and compelling efforts. The Ironman Triathlon has evolved its own mystique becoming synonymous with epic physical efforts and stunning athletic performances. Many of these efforts have been sensationalized by the press and media motivating spectators, endurance athletes, and others to join and aspire to the ranks of multisport endurance athletes. Supporting this growth is an ever expanding array of highly technical equipment including bicycles and components, shoes, clothing, and nutritional systems geared to support novice, experienced, and professional athletes in their pursuit of personal glory. Regrettably, this surge of interest and participation has come at the price of injury; many endurance sport participants, whether first timer, novice, recreational, or professional, have suffered from an injury serious enough to require modification of training, rest and/or medical attention.

Technology alone cannot prevent the occurrence of an injury. Now more than ever, the ranks of triathletes are populated by midlife adults, many of whom are ex-athletes with dormant, hidden, and long forgotten musculoskeletal injuries. While the training required for these events offers the endurance athlete the benefits of cross-training, the long hours of rigorous training coupled with the demands of preparation for multiple sporting activities place the amateur and professional alike at risk of injury. With increasing frequency these athletes fall victim to a whole host of frustrating and sometimes devastating injuries, requiring weeks and sometime months for recovery. Overuse injuries account for up to 78% of injuries suffered by triathletes with injury exposure rates during the 6 months leading up to a competitive season estimated to be 2.5 injuries per 1000 training hours and 4.6 injuries per 1000 training hours during a typical 10-week competitive season. A relatively

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recent summary of injuries suffered by European triathletes estimated that 74.8% of longdistance triathletes suffered from at least one injury. While some of these injuries can be considered acute in nature such as contusions, abrasions, and fractures, the majority of injuries would be classified as overuse injuries impacting the musculoskeletal system. Recent advances made in training systems, nutritional guidelines, endurance supplements/fluid replacements, cycling equipment, clothing, shoes, and foot orthoses have evolved to enhance performances, improve athlete comfort, and reduce the risk injury. Advising and educating the triathlete and the medical specialist providing treatment for the multisport athlete has become a cornerstone for the management of these athletes. In this chapter we will explore the indications, applications, modifications and role of athletic shoes, pedal systems, and foot orthoses for the treatment and/or prevention of lower extremity overuse injuries typically encountered by the triathlete, duathlete, and adventure race participant.

Overuse Injuries

Wolfe's law has had a profound impact on sport, training, medicine, and rehabilitation; it is generally accepted that tissues can adapt and remodel in response to applied stress. However, if the stress and frequency of its application exceeds the immediate or accumulative limits of the tissue and its ability to recover then cellular and tissue damage will occur and an injury will develop. Most frequently these injuries gradually evolve and would be classified as overuse injuries. Numerous circumstances are thought to be associated with overuse injuries including extrinsic and intrinsic factors. Multievent endurance activities are unique and blend several activities, typically swimming, cycling, and running. Each of these activities is associated with a key component of stress.

Cycling cadence and gearing resistance combine through long hours of training and competition can lead to tissue injury, failure, and the development of an overuse injury. Cycling over level terrain at a slow to moderate speed at a mid gear range (39/15) will offer minimal musculoskeletal stress. Most cyclists will generate power from the pedal and crank arm through the drivetrain from the 12 o'clock position to the 6 o'clock position, or during the down stroke of the pedal. A force–time curve for this activity would exhibit a single active propulsion peak of force corresponding to the midpoint between the beginning and end of each power stroke. Active forces are a result of a propulsion system generated by the cyclists' muscular effort, and when increased resistance is met such as during hill climbing or applied as would be the case with gear changes excess active forces will be dissipated in the joints of the lower extremity, hip, and low back. Supporting soft tissues thus serve to generate the power necessary for forward movement, to stabilize joints, and to dissipate excess and harmful stress.

Impact forces with the supporting surface at contact have been linked to the development of running overuse injuries. When running across a level uniform surface at a slow to moderate speed, most runners will exhibit a heel strike running gait. The resulting force–time curve reflects the impact forces generated from heel contact through toe-off and exhibits two peaks. The first, an impact peak represents heel contact and is associated with a steep upslope while the second peak represents an active propulsion peak with a more gradual upslope. Impact forces associated with overuse injury are dissipated through the joints and soft tissues of the lower extremity. Active propulsion forces resulting from the runner moving across the stationary supporting foot are also dissipated through the response of joints and adjacent soft tissues. Both forces have been associated with the development of overuse injuries.

Other forces act on the athlete and may contribute to the development of overuse injuries. While the exact cause for overuse running and cycling injuries is yet to be determined it is postulated that the etiology is multifactorial reflecting a diverse origin. Various factors have been discussed and can generally be organized into intrinsic and extrinsic factors. Training errors, anatomical abnormalities, and lower extremity biomechanics are widely accepted as common factors contributing to the development of overuse injuries. Careful selection of running and cycling shoes may help the athletes to reduce their overall risk of overuse injury and improve upon comfort and performances. Improper, damaged, and/or worn out shoes have been implicated in the development of overuse injuries. Additionally, the manner in which the foot is cradled within the shoe by way of an orthoses can contribute to enhancement of comfort, avoidance of overuse injury, and as treatment for an existing injury.

The Act of Running: Single Support and Double Float (Swing)

The act of running propels the triathlete forward during the running portion of training and racing. Running challenges the triathlete to coordinate simultaneously complex events through an as yet to be fully explained neuromusculoskeletal proprioceptive feedback system embedded in muscles, tendons, ligaments, joints, and skin to (1) establish a stable and adaptable base of support, (2) coordinate balance, minimizing unnecessary oscillations and excessive migration of the center of mass during forward progression, (3) coordinate foot placement to augment the establishment of a stable adaptable base of support, (4) regulate ground clearance of the foot during the swing phase, (5) generate the mechanical forces necessary to accelerate and maintain the forward propulsion of the runner, and (6) dissipate the mechanical energy (shock) resulting from impact and decelerate forward progression of the runner. While running gait is generally considered to be repetitive and predictable individual characteristics contribute to a high degree of individual specificity. Thus, injury changes to the running surface, shoes, orthoses, and even socks may trigger individually unique adaptations to the basic running form and gait cycle.

Running gait, although similar to walking, can be subdivided into two distinct phases: a *stance phase* and a *swing phase*. Because of inherent differences between individuals including stature, body proportions, coordination, joint range of motion, musculoskeletal strength, neuromuscular feedback pathways, proprioceptive abilities, previous injuries, and anatomical variations running gait patterns are unique. However, due to basic anatomic, physiological, and neuromuscular makeup running locomotion is accomplished in a similar manner for all individuals. The act of running is very cyclical, coordinating the alternating and rhythmic actions of the extremities and trunk through a highly automated series of movement patterns which rely on proprioceptive and neuromusculoskeletal feedback to coordinate the interaction of the trunk, arms, lower extremities, and feet to efficiently propel the athlete forward.

The *stance phase* of running gait represents the support period during which time the limb first encounters the support surface and ends when the limb leaves the support surface at toe-off. This phase encompasses approximately 40% of running gait cycle. Stance phase of running can be subdivided into five distinct phases:

1. Initial contact
2. Loading
3. Midstance
4. Propulsive phase also referred to as terminal stance
5. Preswing

The *initial contact phase* of running gait represents the commencement of the stance phase of running. This phase represents the initial contact of the swinging foot with the support surface. This phase may be described as a heel, midfoot, or forefoot contact moment. Most runners will consistently exhibit one of these contact patterns; however, variations may occur during any given run or between runners as a result of anatomical differences, running speed, stride length, cadence, running surface properties, and/or as a result of musculoskeletal fatigue. With increasing speed and certain anatomical or kinematic variations such as might be exhibited by a short limb, limited ankle joint dorsiflexion, tight gastrocsoleus muscle, or short Achilles tendon a runner may be more inclined to contact the support surface distal of the heel. With decreasing speed, reduced stride length, and musculoskeletal fatigue many runners will make initial contact with the support surface through heel contact. The *loading phase* of running represents that crucial period during which time the stance limb begins to dissipate the impact of the body with the support surface. These external forces can be as high as 3–6 times the body weight for the typical runner dependent on individual running kinematics, terrain, running surface properties, and even greater for the older runner. Knee and hip flexion as well as eversion of the heel acted upon by adjacent soft tissue also affects the dissipation of these forces. This phase is dominated by the effects of pronation of the STJ which serves to "unlock" the functional midtarsal joint (talonavicular and calcaneocuboid joints) of the foot and through a coupling action at the talo-cruial joint to internally rotation of the lower leg. *Midstance* represents a crucial phase, one of transition; the stance phase limb continues to dissipate impact forces through pronation acting across the talonavicular joint while adapting to the support surface, shoes, or orthoses. This phase also marks the earliest signs of resupination of the foot.

Forefoot and midfoot contact running alters the loading response and midstance phases of running. This running style rapidly exerts a pronatory load across the oblique axis of the midtarsal joint and by way of pronation of the talonavicular joint indirectly acts to pronate the STJ. Impact is dissipated at the same time the posterior musculature of the lower leg is eccentrically loaded serving to both decelerate impact forces and store elastic energy in the musculotendinous structures.

During *midstance* the foot achieves full contact with the support surface. It is during this phase that the foot reaches its maximum level of pronation and with the assistance of the tibialis posterior muscle in addition to the momentum of the swing leg triggers the resupination of the foot, reversing the effects of pronation. This in effect permits the foot to achieve a stable foundation as the foot prepares to advance to the *propulsive or terminal stance phase of running*. *Propulsive or terminal stance* is established around a stable foundation of a supinating foot. This phase commences at the moment the heel of the stance limb is lifted from the support surface and ends when the finial propulsive forces are exerted through the big toe at toe-off. To achieve the most efficient transfer of energy the foot must be stable, a result of successful resupination of the stance limb. Resupination of the midtarsal joint and STJ is the cornerstone of foot stability; however, rotation of the pelvis generated by the swing leg and the influences of lower extremity muscles contribute to stabilizing the foot. The peroneal longus, flexor hallucis longus, and tibialis posterior muscles all contribute significantly to the establishment of medial column and forefoot stability while the tibialis posterior muscle reinforces the talonavicular joint and resupinates the rearfoot around the STJ.

Preswing phase of running gait is brief; many may even consider it to be nothing more than the terminus of the propulsive phase. Preswing serves to usher in a smooth transition, permitting the stance phase limb to shift its load to the contralateral limb and enter the swing phase of running with a minimal loss of forward momentum and or balance.

The *swing phase* of running is the period during which the foot and limb "unwind," becoming realigned in preparation for a new stance phase cycle. This phase should be considered as the period after the support limb leaves the support surface at toe-off and continues until the contralateral limb encounters the support surface at *initial contact*. This phase encompasses 60% of the running gait cycle. Swing phase of running can be subdivided into three distinct phases:

1. Initial swing
2. Midswing or double float (up to 30% of swing phase)
3. Terminal swing

Initial swing phase immediately follows preswing (toe-off). During this phase the foot continues its resupination and begins the realignment of the hip. However, the hallmark of the swing phase is *Midswing,* a period of *double float*. Unique to running, midswing represents a period when both limbs are suspended above the support surface as if floating. Depending on cadence, stride length, and the characteristics of the supporting surface this period may vary in its duration. During this phase the trailing limb is recovering from stance phase actions while the leading limb is preparing for initial contact. *Terminal swing* represents the finial resupination of the leading limb, initial contraction of muscles critical to dissipation of impact forces, and stabilization of joints critical to initial contact such as the hip, knee, ankle, and STJ.

The Act of Cycling: Spinning Through Power and Recovery Phases

Forward propulsion is typically generated by the cyclist through pressure applied to the bicycle drivetrain. The drivetrain is composed of the pedal, crank arm, bottom bracket, ring gear, chain, derailers, and rear sprocket (cassette). When seated or standing the cyclist will move the pedals and crank arm through a 360° circular path or *pedal cycle*. The typical triathlete will ride or *spin* (a high uniform cadence) at a cadence which repeats the pedal cycle from 60 to 100 revolutions per minute (RPM) generating up to as many as 6000 pedal cycles per hour and 38,000 pedal cycles in a typical Ironman Triathlon. When the lower extremity is exposed to pedal cycle frequencies at this level even minor biomechanic abnormalities, musculoskeletal imbalances, and altered joint range of motion can manifest into overuse injuries.

The pedal cycle is divided into two phases: the *power phase* and the *recovery phase*. When applied in sequence these two phases will generate the power necessary to propel the cyclist forward. The *power phase* is defined as the period which extends from the pedal starting position at "*top-dead-center*" (TDC) with the pedal at 0/360° and rotating clockwise to "*bottom-dead-center*" (BDC) with the pedal ending at 180°. It is during this phase that most cyclists will generate the majority of the power necessary to propel the bicycle forward. The *recovery phase* immediately follows the power phase and is defined as the period which extends from the pedal at BDC with the pedal at 180° and rotating clockwise back to TDC. During this phase the cyclist realigns the foot and leg and the power generating muscles are provided with an episode of rest or recovery before the next power phase. When cyclists use cleated shoes with a clipless pedal system, the recovery phase may also contribute significantly to recovery phase power transfer as the cyclist exerts an upward pull upon the pedal and crank arm through to the TDC position and the beginning of the next power phase. However, the primary biomechanical role of this phase remains one of realignment, returning the foot, knee, hip, and back to return to position which is more optimal for generating the next power phase.

A complex interaction of lower extremity joints and muscle activity act to provide forward propulsion for the cyclist. During the power phase the hip and knee extend, the ankle remains neutral or plantarflexes, and the foot pronates. Augmenting these joint actions are muscles of the lower extremity and back acting upon the hip including the gluteal muscles which extend the hip, the paraspinal muscles which stabilize the pelvis and low back, and the hamstring muscles which act to assist the gluteal muscle during extension of the hip. The quadricep muscles act upon the knee to extend the leg, providing most of this effect in early power phase while the hamstring muscle continues knee extension in late power phase. The ankle which typically oriented in a slightly dorsiflexed position at TDC begins to plantarflex in the power phase under the influence of the soleus muscle and is continued past BDC by the action of the gastrocnemius muscle and the flexor hallucis longus muscle.

The effect of the calf muscles and the deeper flexor hallucis longus upon the ankle joint is important to the transfer of power from the leg to the pedal and drivetrain of the bike. These muscles perform to resist hip and knee extension forces through a stabile ankle, provide propulsive power especially during the later stages of the power phase, and place the foot in a neutral to slightly plantarflexed position at BDC augmenting the ability of the hamstring muscles to carry power across BDC into the recovery phase of cycling. Gregor and Okajima observed that the most effective transfer of power from the foot to the pedal and drivetrain occurred when the foot (force) was applied perpendicular to the crank arm.

Pronation of the foot occurs during the power phase of cycling. As force is applied by the extending leg to the foot the resistance of the pedal and drivetrain triggers STJ and MTJs to pronate. This action leads to eversion of the forefoot, dorsiflexion, and inversion of the medial column and abduction of the forefoot. This may result in an eversion moment of the rearfoot at BDC.

Translocation of the knee in the transverse plane occurs as the knee extends through the power phase. This motion is dependent upon pelvic width, Q-angle, and the pedal–crank arm width. Typically as the knee extends it moves closer to the bicycle since the foot is fixed to the bicycle by the pedal. Excess *Q*-angles can further perturb the adduction of the knee during the power phase and may represent a significant contributing factor to overuse injury of the knee. Furthermore, abnormal function of the vastus lateralis and rectus femoris may further contribute transverse plane abnormalities by displacement of the patella too laterally when opposed by a weak vastus medialis muscle.

The recovery phase of cycling serves to realign the lower extremity. The limb moves from BDC to TDC as the hip and knee flex, the ankle dorsiflexes, and the foot resupinates. Cyclist that ride with cleated shoes and pedal systems may use the recovery phase as a power generating phase to augment forward propulsion of the contralateral limb. Under these circumstances the recovery phase limb is acted upon by the hamstring and gastrocnemius muscles. Late in the recovery phase the anterior tibial muscle will begin to dorsiflex the ankle while the quadricep muscles continue to flex the hip and begins to extend the knee.

Biomechanic Role of the Foot

Root et al. proposed a Subtalar Joint Neutral Theory to classify the foot, basing this theory on subtalar joint (STJ) neutral position and a fully pronated midtarsal joint. This system, although dated, classified structure, function, and functional relationships of the foot and the lower extremity; it remains the most comprehensive and widely applied system with which to classify the foot and its biomechanics. This theoretical and conceptual model of foot function has undergone relatively little change since its first introduction; however, it has spawned several alternative theories which also strive to explain the function of the foot and more importantly the influence of foot orthoses upon the symptomatic lower extremity. These theories include the "Tissue Stress Theory," "Sagittal Plane Facilitation of Motion Theory," and "Preferred Movement Pathway Theory".

Root et al. described the ideal or normal foot, its function, and based upon the STJ Neutral Theory a system of classification how the symptomatic foot should be supported with foot orthoses. Central to the STJ Neutral Theory is foot function which is most efficient around a neutral STJ with the midtarsal joints "locked" in a maximally pronated position. By accomplishing this, the foot orthoses would (1) limit extraneous motion, control the foot around the STJ neutral position during gait, (2) minimize potentially harmful compensation(s) by the foot for lower extremit abnormalities, and (3) induce a strong "locking" action of the midfoot across the midtarsal joints.

Unfortunately, this STJ Neutral Theory of function has not been adequately tested and limited evidence exists to support the concept that to remain injury free the foot must function around the STJ neutral position. (John Weed, 1985–1992, Personal communications). Yet, convincing clinical evidence exists to suggest that patients treated with foot orthoses constructed upon a model of the foot in the STJ neutral position tolerate the orthoses well and symptoms improve. The lack of clinical and research evidence validating the STJ Neutral Theory has stimulated research to explain functional and mechanical action of the foot.

Alternative theories have been proposed in an effort to better explain foot function and the impact of foot orthoses. Each of these theories recognizes that a unique STJ axis of rotation exists and that foot orthoses directly or indirectly influences the motion at this joint. The *Tissue Stress Theory* proposed by McPoil and Hunt strives to associate treatment of injuries with orthoses as a process of assessment leading to orthoses management directed at the compromised anatomical unit or tissue. McPoil and Hunt suggest that by utilizing the Tissue Stress Theory the clinician will have a better system from which to develop a system of examination and management of individual foot disorders. The Tissue Stress Theory should allow clinicians the opportunity to more accurately develop a prescription for a foot orthoses which meets the anatomical/structural needs of an injured tissue rather than developing an orthoses prescription based upon unreliable measurements.

The *Sagittal Plane Facilitation of Motion Theory* described by Payne and Dannenberg hypothesizes that functional limitations of hallux dorsiflexion during the propulsive phase of gait may be responsible for abnormal foot function and complaints of pain. Fundamental to this theory is the functional performance of the first metatarsal phalangeal joint; when hallux dorsiflexion is restricted during the propulsive phase of gait the foot will compensate by way of abnormal movement patterns which contribute to the development of injuries and complaints of pain. Payne and Dananberg postulate that when the "sagittal plane" motion (dorsiflexion) of the hallux is reestablished through the introduction of foot orthoses a normalization of timing, movement patterns, and plantar pressures will occur throughout the lower extremity. Recent evidence suggests that functional hallux limitus may trigger a retrograde response mitigated by other structural units or functional pathways. However, central to this theory remains the limitation of hallux dorsiflexion at the first metatarsal phalangeal joint complex.

The *Preferred Movement Pathway Theory* proposed by Nigg et al. attempts to describe foot orthoses performance based upon a complex sensory feedback loop which serves to modify muscle activity. A fundamental premise of this theory centers on the changes observed in muscle activity when foot orthoses were introduced. Nigg et al. observed that the joints and of the foot exhibited a preferred movement and activity pathway. However, when foot orthoses were introduced, joint movement pathways persisted but muscle activity was minimized. Through a proposed sensory feedback loop the foot orthoses served to tune the muscles and thereby dampen potentially harmful soft tissue vibrations.

In an attempt to explain the motion of the foot around the STJ Kirby proposed a technique to illustrate the spatial location of the STJ. Kirby concluded that an abnormal position of the axis of rotation of the STJ had a significant influence upon the function and performance of the foot. Abnormality of the spatial position of the axis of rotation of the STJ may occur in the transverse and/or sagittal planes. Assuming planal dominance of motion, deviations of the axis of rotation in the sagittal plane will alter the magnitude of either the transverse or frontal plane components of the motion. Kirby, however, recognized that medial or the lateral shifts of the axis of rotation of the STJ in the transverse plane would significantly effect the function and performance of the foot. The *Subtalar Joint Axis Location and Rotational Equilibrium Theory* of foot function was proposed to explain these effects and described three foot types: *medially deviated STJ axis, normal STJ axis*, and *laterally deviated STJ axis*. This theory recognizes that the influence of weight-bearing activities upon the foot may vary dependent upon the spatial location of the STJ axis of rotation.

Anatomy of a Triathletes Running and Cycling Shoes

The Running Shoe

Since its inception over 40 years ago the modern running shoe has undergone an evolution of change driven by the needs of the athlete. Today's distance training and racing shoes are technically advanced with designs to suite nearly every foot type (pes cavus, neutral, and pes planus), anatomical circumstance (adducted foot, rectus foot, heavy runner, wide foot narrow foot, etc.) and running need (cushioning, neutral, stability, motion control, bare foot, and racing). Design characteristics of running shoes have been demonstrated to influence running kinematic variables of the rearfoot including foot position at contact, peak eversion, and peak eversion velocity. While it is widely held that the potential for developing an overuse running injury is reduced with careful running shoe selection, no clinical data is available to date to support this hypothesis. However, the importance of selecting a

Fig. 16.1 Reebok women's running shoe

well-designed running shoe is unequivocal; comfort, function, and fit are all enhanced when the triathlete selects a shoe based upon functional needs as well as training and racing demands.

The anatomy of a typical running shoe is composed of several coordinating components (Fig. 16.1):

Upper
Closure (Lacing) system Midsole
Outsole
Sock liner/foot-bed

The shoe *upper* which cradles the foot can be subdivided into a toe box, vamp, throat, collar, and heel cup. The *closure (lacing) system* serves to secure the shoe to the foot in a manner not to adversely impede function and comfort. The *midsole* acts to dissipate the forces of impact during the stance phase of gait and it acts to augment the transfer of stance phase forces through the lower extremity during the act of running. It is composed of a cushioning component which may include specialized stabilizing support units, thermal plastic units, and various specialized impact absorbing and force dissipating components. The *outsole* of the shoe is composed of a durable material with a sheet-like or modular pattern which promotes additional cushioning, support, and traction without sacrificing the transfer of stance phase forces through the lower extremity. The *sock liner/foot-*bed is the removable surface which serves to support the foot. It is typically composed of a fabric-covered and cushioned material molded to the shape of the foot which serves to promote a comfortable fit while wicking moisture and dissipating friction. It may also act to augment midsole cushioning and the transfer of stance phase forces through the lower extremity.

The modern running shoe can trace its roots back over four decades to the innovations and design concepts first explored by Coach Bill Bowerman of Oregon; however, the modern running shoe now more adequately blends anatomical form with biomechanic function. The modern running shoe is built around a model of the foot or *last*. While each shoe manufacturer maintains their own unique lasts, all lasts can be organized into one of three general categories based upon the shape of the last. A *curve last* has a distinct "*C-shape*," and when bisected by an imaginary line extending from center of heel through the forefoot more of the shoe will appear medial to the bisection. This is easily viewed when the shoe is examined from the bottom of the outsole. Curve-lasted shoes are best suited to runners with a normal to cavus foot type with adduction of the forefoot. A *straight last* is characteristically straight, and when bisected from center of heel to forefoot the shoe is divided into two nearly equal halves. These shoes are best suited to runners with a normal to pes planus foot type with a more abducted forefoot. A *combination last* represents a hybrid of a curve last and straight last; the rearfoot portion of the shoe is straight while the forefoot portion of the shoe is more curved. When bisected this shoe appears straight through the rearfoot and midfoot with a slight tendency to be adducted through the forefoot. This last best suits the widest range of foot types.

Running shoes can also be categorized by the method of construction. *Slip lasts* are constructed in a manner that secures the upper of the shoe at the midsole with a serpentine stitched line. These shoes afford the maximum degree of flexibility and the lowest level of overall stability. A *board last* shoe applies a fiber board from heel to toe which is glued to the upper where the upper joins the midsole. This construction is inexpensive and affords the greatest degree of heel to toe stiffing and overall resistance to longitudinal torque. A *combination last* blends the advantages of slip and board last construction by securing the rearfoot portion of the shoes upper to the midsole via a fiber board or stiffener leaving the forefoot serpentine stitching exposed. This construction is very popular and has undergone refinements which have integrated the rearfoot stiffener directly to the upper not by direct gluing but rather by stitching the stiffener perimeter directly to the upper at the union with the midsole. This shoe construction provides a reliable and stable rearfoot while maintaining forefoot flexibility without sacrificing longitudinal stability. These refinements to the classical combination last have permitted shoe designers to integrate the shoe upper with the lasting permitting a more effective coupling of upper to midsole.

The most visible component of the modern distance running shoe is the upper. The upper is composed of a breathable tough and lightweight material which is reinforced with various swatches of synthetic leather to promote structural integrity, medial–lateral sway stability, and to enhance forefoot flexibility at heel off through toe-off. A handful have improved lining designs to the point that all interior seams have been eliminated. This is a significant advantage for the athlete who is susceptible to blistering. Likewise shoe tongue designs have improved balancing padding without excessive bulk. Traditionally a U-shaped throat has been utilized; this design is highly tolerant to a wide variety of midfoot anatomies ranging from the cavovarus foot to the low pes planus foot type. Various lacing systems have been employed but the variable lacing system is the most popular and functional. This system easily adapts to the introduction of a speed lacing system using elastic laces or a lace lock system.

The midsole of the distance running shoe has undergone the greatest evolution. The modern midsole is constructed from a variety of cushioning materials, stabilizers and support components, or *thermal plastic units* (*TPU*). The role of the midsole is to absorb and dissipate impact, stabilize the foot, and enhance the forward progression of the runner. Ethyl vinyl acetate (EVA), polyurethane (PU), sealed oil and gel chambers, and sealed air chambers represent the most common materials used. Each of these materials comes in a range of firmnesses, and unique placement into the midsole will impart specific cushioning, flexibility, and movement transfer abilities to the shoe. Typically softer cushioning materials are placed under the heel and forefoot for cushioning while firmer materials are positions under the medial heel extending into the midfoot and forefoot to promote enhanced stability. These materials are also frequently wrapped up onto the shoe upper at the transition zone between shoe upper and midsole to promote medial–lateral stability and to increase longitudinal stability. TPUs of various sizes and shapes are typical to most midsoles; these inserts serve to promote stability, act as a rearfoot to forefoot bridge, and guide the foot through the gait cycle.

Outsole technology is dominated by modular designs. Durability, traction, and grip are primary goals for shoe outsoles, especially given the variety of surfaces over which the distance runner will pass. However, the unique placement of outsole modules of different firmness, materials, and density can also enhance heel contact cushioning, guide the foot through midstance, and maintain forefoot flexibility at heel and toe-off.

The Cycling Shoe

The cycling shoe is unique among athletic shoes and serves to integrate the foot and lower extremity with the crank arm and drivetrain of the bike by way of the pedal. The typical cleated cycling shoe is designed around an adducted last which is comparable to a 2–4 in. dress heel. The typical European designed cycling shoe also tends to be narrower than their domestic counter parts. However, the anatomy of a typical triathlon cycling shoe is standard and can be subdivided into four primary areas of importance:

Upper
Closure system
Sole/cleat anchor
Sock liner/foot-bed

Similar to running shoes, comfort and performance can be enhanced when triathletes carefully select training and racing shoes.

The *upper* of a cycling shoe is typically composed of leather, man-made synthetic leather substitutes (such as Lorica), synthetic fabric (nylons or polyesters), or a combination of materials. Backing materials may decrease irritation at pressure points but can also serve to increase internal heat and retention of moisture. The upper of the shoe should conform securely to the foot without excessive pressure points across critical anatomical structures (such as first and fifth metatarsal phalangeal joints) and promote adequate ventilation to avoid the buildup of excessive heat and moisture (perspiration) around the foot. The toe box and vamp shape should be adequate to fit the forefoot without crowding the toes unnecessarily, yet be adequately streamlined for efficient aerodynamics at higher speeds. Unlike running shoes most training and racing shoes suitable for triathlons will anchor the upper of the shoe directly to the sole. Additional stability may be achieved through the addition of TPU at critical stress points such as the forefoot and heel. The heel counter of the shoe will incorporate a firm heel cup composed of a thermoplastic material with light interior padding and a padded collar for comfort and to maintain a secure rearfoot fit.

Securing the shoe to the foot requires a *closure system* which is easy to use, adaptable to a variety of foot types, easy to use, and easily adjustable in transition and/or during training and racing. Multiple closure systems have evolved, one to three hook and loop straps and/or ratchet buckles are durable, secure, and easy to use. Strap systems which utilize hook and loop (Velcro) to secure the strap to the shoe have the advantages of reliability, ease of use, more adjustment possibilities, and speed of use. Unique to triathlon shoes are straps which are anchored laterally to the shoe and adjustable medially. This helps to keep loose "flapping" straps free of crank arms, bottom bracket, spinning wheels, and spokes.

The *sole* of the cycling shoe serves as the rigid link between the foot and pedal/crank arm and drivetrain. Typical outsoles are composed of a molded thermoplastic (nylon) material, carbon graphite, and molded thermoplastic reinforced with fiberglass. Rigidity, cleat mounting pattern, heel post, toe break angle, and stack height are all important characteristics to consider when selecting a cycling training or racing shoe. Carbon graphite soles offer the greatest rigidity while molded thermoplastic soles offer greater flexibility. While a rigid sole is important for efficient transfer of power from the lower extremity to rotational torque in the crank arms it may also prompt a more awkward running/jogging gait during triathlon/duathlon transition. Cleat mounting hardware is incorporated into the sole of the shoe and serves as the anchoring site for the pedal cleat. Anchor patterns may vary, some are unique to specific cleat–pedal systems while others may be more universal suitable for a wide variety of cleat–pedal systems. All anchoring systems approximate cleat placement at the metatarsal phalangeal joints and should permit cleat placement adjustment to suit the specific needs of individual cyclists. A heel post/pillar is typical to most shoes and serves to ease walking in cycling shoes, relieve strain on the Achilles tendon during walking, and provide limited protection to the sole. Running out of and into transition areas is awkward for the triathlete; to ease this brief run the triathlete may wish to consider a cycling shoe of a thermoplastic nylon or nylon reinforced with fiberglass sole to permit slight sole flex to ease an awkward run and to avoid running out the back of a more rigid sole shoe.

Toe break angle and *stack height* are two variables unique to cycling shoes. Toe break angle is the degree of rise of the forefoot of the shoe. Shoes with greater toe break angles may permit the cyclist to generate greater power during the power and recovery phases of cycling and ease muscular fatigue. A moderate toe break angle will permit the downward force applied by the extending lower extremity to the crank arm to remain closer to perpendicular to the crank arm, thereby achieving a more efficient transfer of force to rotational torque as the ankle plantarflexes through late power phase. However, high toe break angles will preload the plantar fascia and potentially increasing its intrinsic tension through excessive tightening of windlast mechanism increasing the potential for plantar (fascia) forefoot pain. Stack height of a cycling shoe may vary by brand, model, and design. It is the thickness of the sole of the shoe at the cleat attachment point measured in millimeters. By maintaining the foot close to the pedal axle power transfer during both the power and the recovery phases of cycling will be enhanced. Higher stack heights are more typical of molded thermoplastic nylon soles which require greater thickness to achieve sole rigidity. Carbon and carbon composite soles achieve equal to greater sole rigidity while maintaining low stack heights and can improve the overall shoe pedal–drivetrain efficiency. High stack heights may adversely impact the triathlete during run transitions in cycling shoes. During the brief run through transition, a high stack height can potentially dorsiflex the foot at the ankle increasing the concentric tension imparted upon the Achilles tendon and calf muscles. High stack heights can also increase the potential for lateral instability of the foot and ankle during run transitions.

A shoe *foot-bed or sock liner* is typically a thin and protective liner which separates the plantar surface of the foot from the interior of the shoe. This liner should be removable to permit replacement of the liner with a more efficient custom or prefabricated foot orthoses. However, when for those triathletes not requiring foot orthoses these liners should help to dissipate heat buildup, improve ventilation through sole, provide minimal cushioning, and carry moisture and perspiration away from the skin of the foot.

Classifying Running Shoes

Numerous guidelines for the categorization of running shoes have been circulated in the popular press. The following list of general categories is the most widely accepted and used for running shoes:

Cushioning
Neutral
Stability
Motion control
Racing

Considerable overlap may exist; shoe authorities and manufactures may disagree on the assignment of a shoe to a category. However, based upon long-standing use and acceptance by the public this system provides a good starting point for the selection of an optimal training and racing shoe for the triathlete.

Shoes for *cushioning* represent designs which emphasize cushioning and flexibility. These shoes typically possess a uniform density midsole, limited shoe stabilizing add-in features, and an outsole which promotes flexibility while maintaining good traction with the support surface. These shoes promote an efficient running gait and rely on normal lower extremity and foot biomechanics. These shoes are best suited for the efficient lightweight runner with a normal to high-arched foot who demonstrates normal lower extremity biomechanics. The *neutral* shoe represents a design which promotes adequate cushioning, flexibility with the addition of limited stabilizing features. These shoes are best worn by a lightweight runner who exhibits normal lower extremity biomechanics. *Stability* running shoes are designed with the intent to augment the natural stability of the foot through all phases of gait. These shoes emphasize adequate cushioning and forefoot flexibility and enhanced motion controlling properties. These shoes are best worn by lightweight through normal weight runners with normal through moderately abnormal lower extremity biomechanics. Runners with normal foot biomechanics may elect to use this shoe to promote greater stability, especially during runs when fatigue influences normal running gait. *Motion control* shoes are intended to promote a maximum level of support and influence under the most extreme levels of excessive pronation of the foot during all phases of the running gait cycle. These shoes are better suited for runners with low-arched or a pes planus foot type and work well for individuals competing in the heavy weight class. These shoes are generally poorly suited for the lightweight runner due to the presence of very firm midsole materials which can promote excessive resistance to the normal foot function. *Racing* shoes represent a very special classification of running shoe; these shoes are intended to be lightweight and generally are poorly suited for the average triathlete.

Design innovations are frequently introduced to existing shoe models or shoe line-ups; however, rarely are entirely new design concepts introduced. However, Nike with introduction of the *Nike Free* brought to the running community an entirely new shoe classification. These shoes are designed as training or racing flats which intend to simulate the act of running barefoot while still proving adequate protection from foreign objects. These shoes do offer the triathlete with a training shoe to augment the strengthening of intrinsic musculature, otherwise not strengthened in a traditional shoe. However, these shoes provide little in the way of support for a foot which exhibits excessive pronation or for the runner which exhibits pronation of the foot through the midstance and propulsive phases of gait.

Finding the Perfect Triathlon Shoe

Finding the best training or racing shoe can be a formidable task. Numerous options exist; each shoe type and category is rich with near equal choices and each manufacture provides proprietary technology designed to enhance each run or ride; considerable overlap exists between manufacturers promoting shoes within any given category. The process of selecting a suitable running shoe can be enhanced by following a few simple rules:

Examine shoe for appropriate last shape
Examine shoe for neutral position
Examine shoe forefoot flexibility
Examine shoe midfoot torsional stability
Examine shoe heel counter rigidity
Examine shoe upper side-to-side stability
Examine shoe lacing system
Examine shoe outsole traction
Examine shoe last for orthoses fit

A few moments spent examining a new shoe can prevent the selection of a poorly constructed, designed, or possibly mismatched training or racing shoe.

To achieve an optimal fit, match the shape of the foot to the *shoe last shape*; fit an adducted foot and or cavus foot type to a curve-lasted shoe, a low/flat-arched pes planus foot type to a straight-lasted shoe, and fit the normal foot type to a combination-lasted shoe. The modern running shoe is built around a *neutral position* which places the heel counter of the shoe perpendicular to the support surface. Evaluate a shoe for neutral position on a flat and level surface; heel counters which are inverted or everted will impose an abnormal influence upon the foot through heel contact and can adversely effect the intended influence of foot orthoses throughout the gait cycle. Unnecessarily stiff or too proximal *forefoot flexibility* will increase the resistance to heel off leading to excessive momentary loads to the metatarsophalangeal joints and to the distal expansion of the plantar fascia. *Midfoot torsional stability* permits the rearfoot and forefoot to function independently in the frontal plain, yet provide resistance to sagittal and transverse plain movement. Excessive midfoot flexibility may increase the risks of overuse injuries linked to excessive and prolonged midstance and propulsive phase pronation of the foot. *Heel counter stiffness* relates to the rigidity or compressibility of the shoes rearfoot. Shoes with greater heel counter stiffness promote enhanced rearfoot stability at heel contact through midstance phases of gait. Heel counters with greater stiffness also provide a stabilizing influence to foot orthoses; enhancing orthoses heel cup influences directly to the foot and by providing a firm barrier against which the foot orthoses rearfoot posting may establish a predictable seating and a surface from which to establish leverage. *Shoe upper (vamp and quarter) side-to-side stability* is critical to maintaining the foot directly over the outsole and midsole of the shoe during all phases of running gait and under all circumstances of running surface and terrain. Excess shoe upper side-to-side movement will increase the risk of both chronic overuse injuries and even acute inversion (foot and ankle) injuries. Stable shoe uppers are well reinforced and exhibit minimal transverse plain (side-to-side) shift when stressed. Securing the shoe to the foot is the role of the *shoe lacing system*; important features for the triathlete to consider include adequate variability to the lacing system to suit the specific needs of the athlete, suitability of the lacing system to the introduction of elastic or speed laces, and a design which avoids pressure points across the dorsum of the foot. Triathletes train year round and under a wide variety of conditions. In many regions of the world training may occur on slippery, wet, or icy conditions providing far less than optimal footing and traction. Careful inspection of *outsole traction* design patterns and outsole composition should be considered when selecting a training/racing shoe. Bill Bowerman, Coach Oregon State University, was the first to introduce the waffle sole pattern which has given rise to a myriad of outsole designs. While waffle-type soles provided superb combination of flexibility and traction; its lack of surface area compromises its stability and traction on firm and slippery or icy surfaces. Mixed high–low horizontal and diagonal patterns with crisp edges and traction and flex channels will provide better traction on firm surfaces with poor traction but will become unsuitable when traction is required such as when running on trails. The firmness of the outsole will also influence flexibility, traction, and wear potential. Hard firm materials promote the greatest durability but may sacrifice traction, cushion, and flexibility while softer materials sacrifice durability. Most modern training shoes will accept foot orthoses; however, special considerations should be made for the *suitability of the shoe to accommodate a foot orthoses*. Shoes which will eventually be used with a foot orthoses should provide a versatile lacing system, alternatives to secure the rearfoot snuggly, adequately deep heel cup and rear quarter, removable sock liner, flat stable insole, torsional stability, minimal instep cut out, and adequate width and length. Many times the introduction of a foot orthoses will increase the shoe size need (length) by one half size.

When carefully selected, a well-designed cycling shoe can shave seconds off an athlete's finishing time and help the athlete to avoid injury. While overlap exists between running shoes and cycling shoes, such as *last shape*, *neutral position*, *heel counter rigidity*, *and orthoses suitability*, features unique to cycling shoes should be considered separately when selecting a cycling shoe:

Examine shoe upper for comfort
Examine shoe closure system
Examine shoe sole for stability
Examine shoe for cleat anchoring
Examine shoe toe break and stack height

The heart of every cycling shoe is a *comfortable upper* that snugly fits to the foot without contributing to pressure points, promotes good air flow through the shoe, and minimizes irritating internal seams. The triathlete should carefully examine the *closure system* for durability, ease of use, adjustability, and security. A stable sole is critical for the transfer of power from the lower extremity to the bike drivetrain; examine the cycling shoe for *longitudinal and torsional stability*. The sole should resist torsional flexion when a twisting force is applied especially during climbing and sprinting out of the saddle. While longitudinal flexion will ease running and walking through transitions zones too much flexion will sacrifice power transfer to the bicycle. Avoid cycling shoes that permit longitudinal flexion. Examine the shoe sole for proper *cleat anchoring*; a secure and adjustable anchoring site/system that fits to the intended pedal system is important to optimize power transfer, comfort, and minimize the potential for overuse injuries of the foot, knee, and hip. Examine the shoe sole for *toe break angle and stack height*; avoid excessive toe break angles which may enhance power transfer when pushing big gears but are not well suited for spinning in lower gears as is more typical to triathlon training and racing. Avoid excessive stack height, by keeping the pedal/cleat close to the shoe sole power transfer from the lower extremity to the bicycle drivetrain will be improved through all phases of riding.

Pedal and Cleat Systems

No discussion of cycling shoes should go without a brief discussion of pedal systems. Pedals serve as the link between the cycling shoe and the crank arms of the bicycle. Careful selection of a proper pedal system has been shown to reduce overuse injuries of the knee. *Float* is a terminology used to describe the ability of the cyclists foot to rotate in the transverse plain or for the shoe to be adjusted upon the pedal (in-toed or out-toed) to suite the structural/anatomical needs of the cyclists. *Clip-type* pedals into which the forefoot slips allow the foot to move side-to-side and to rotate in the transverse plane with limited resistance. However, this method of securing the foot to the pedal is inefficient and permits a significant loss of power during both the power and the recovery phases of the pedal cycle. *Clipless* pedals secure the foot directly to the pedal minimizing the loss of power during both phases of the pedaling cycle. Some clipless pedal systems permit the rider to adjust the angle of *float* necessary to achieve a neutral position of the lower leg (patella) to the pedal axle. Three basic systems are available and include unrestricted float, limited float, and fixed float angle; each permit transverse plane (in-toe or out-toe) adjustments of the shoe/cleat position in relationship to the pedal axle and when properly adjusted can reduce lower extremity overuse injuries resulting from transverse plane malalignment of the lower extremity. These pedal systems are especially effective when applied to reduce chronic overuse and torque strain exerted upon the knee and hip during the power phase of cycling. Common overuse injuries such as patellofemoral pain syndrome and iliotibial band syndrome will often respond favorably to a properly fit pedal system.

Socks for the Triathlete

Socks are often one of the most frequently overlooked pieces of sporting equipment/apparel; in our zeal to run and ride triathletes too often discount the potential benefit derived from the garment enveloping the foot. Over 30 years ago DuPont developed synthetic fibers which ushered in an era of *technical knitwear*. Today, this specialize off shoot of the sock and fiber producing industry has created wide variety of very specialized socks and sock fiber blends. When carefully selected the athlete is assured of a sock that will perform under the stresses of both running and riding.

The primary role of athletic socks is to protect the exercising foot from excess moisture accumulations, such as perspiration or extrinsic moisture (rain and spray/mist stations), promote padding, accommodate anatomical irregularities, reduce pressure, and reduce friction and torque forces. The military has long held to the recommendation of a two-sock system to minimize the occurrence of friction blisters. The military has exerted a considerable effort to evaluate socks and boots in an effort to identify the best boot–sock system. Herring and Richie observed that sock fiber-type and sock construction properties could be linked to the frequency, size, and severity of friction blisters among runners, and with careful sock fiber and construction selection the frequency of potentially disabling friction blisters could be reduced. More recent evidence from the Office of Navel Research has associated the development of more serious lower extremity injuries including overuse injuries with military recruits suffering from frequent friction blister events. Based upon these data alone the triathlete should carefully examine the intrinsic and extrinsic circumstances associated with running and cycling in an effort to select an optimal sock to reduce the risk of skin and thereby other musculoskeletal injuries.

Sock fibers can be grouped into two primary categories: natural fibers such as wool, cotton, and silk and man-made fibers such as acrylic, nylon, polyester, and polypropylene. Natural fibers have long been touted for their overall ease of handling, wearability, durability, and ease of cleaning. Man-made fibers (*synthetic fibers*) on the other hand offer a wider range of thermal and moisture management properties as well as providing fibers of excellent wearability, comfort, and durability. Each fiber possesses unique properties; the primary properties include fiber length, tenacity (strength), flexibility, extensibility, elasticity, and cohesion while the secondary properties include fiber resiliency, cross section, surface geometry, specific gravity, and moisture regain. When woven into yarns and knit into technical knitwear the resulting sock will exhibit characteristics consistent with the fiber content and fiber proportionality. For triathletes the properties of moisture and thermal management, cushioning, and the dissipation of friction and shearing forces are important attributes to seek in a technical sock.

The human foot exhibits a significant potential to produce perspiration. The human foot possesses approximately 3300 eccrine sweat glands per square inch or approximately 200,000 eccrine sweat glands per foot. At rest the human foot is capable of producing approximately 1/4 cup of sweat in a 12-h period. With vigorous activities, such as running and cycling, the triathletes' foot may produce vastly more perspiration in the same 12 h dramatically increasing the potential risk for friction blisters. This risk can be reduced by selecting socks which contain a high percent of *CoolMax* fibers; these *synthetic polyester* fibers are specially designed to minimize moisture regain (absorption) and possess a four-channel cross section which enhances the wicking potential of the sock. *Polypropylene* is another frequently encountered synthetic sock fiber used to manage moisture; however, due to these fibers' extreme *hydrophobic* tendencies it can trap excess moisture on the skin and limit the wicking of moisture away from the skin and increase the risk of friction blisters. *Synthetic acrylic* fibers are also excellent fibers from which to make athletic socks. These fibers offer the distinct advantage of a soft feel, comfort, durability, and excellent wearability, but due to the fibers' low moisture regain (absorption) and limited moisture wicking abilities they may leave the foot feeling slightly damp. *Merino wool* is an excellent natural fiber from which athletic socks are knit. Unfortunately, these wool fibers exhibit moderately high extensibility (stretch), poor overall elasticity (return to original shape during vigorous use), and moderately high moisture regain (absorption). The best sock would benefit from the properties of CoolMax, Merino wool, and acrylic blended together into one sock. This sock would exhibit the thermal benefit and moisture absorption properties of wool, the moisture wicking and low moisture regain properties of CoolMax, and the wearability and durability of acrylic.

Sock construction and design is as important to injury avoidance as fiber composition. Three basic design constructions are used and include *flat knit* construction, *Terry-loop* padded construction, and *double-layer* construction. A fourth construction, *Anatomically correct toe-socks*, is also available and may represent an excellent choice for a triathlete who suffers from frequent interdigital friction blisters. A flat knit construction offers only the advantage of a very low bulk sock, potentially an advantage in a tight-fitting cycling shoe; however, this design lacks the ability to absorb the friction and pressure forces associated with friction blister formation. Terry-loop padded construction provides the cushioning potential to dissipate friction and pressure, thereby reducing the risk of friction blisters. Socks of this design come in a range of padding bulks and anatomical alignment of the Terry-loop padding. Finally, double-layer sock construction utilizes two flat knit socks knit together at the cuff and toe to provide slightly greater cushioning potential and dramatically improved friction management without unnecessary sock bulk. For triathletes with a past history of friction blisters to the toes and feet the double-layer sock or lightly padded Terry-loop sock would provide the best potential to prevent an unanticipated skin injury.

Foot Orthoses Success

Foot orthoses for the triathlete can represent a diverse spectrum of externally applied devices, ranging from simple *over the counter* (OTC) arch supports to custom fabricated *ankle–foot orthoses* (AFO). The intended goal of any foot orthoses may be variable and dependent upon the specific needs of the athlete including (1) to enhance/achieve comfort during training and racing, (2) to limit abnormal lower extremity biomechanic events, (3) to enhance efficient running and cycling, (4) for the treatment/avoidance of injury, and (5) to improve shoe fit and performance. The most readily available foot orthoses are prefabricated OTC devices intended to replace the sock liner provided with a new running or cycling shoe. These devices come in a diverse array of designs and sizes intended to fit a generalized "average" foot. OTC devices are typically introduced to augment the properties of a shoe to enhance shoe fit, to improve local cushioning properties, and/or to improve the support of the foot. OTC devices are frequently beneficial and represent an important add-in to any new shoe fitting plan or as part of a more comprehensive plan of treatment for an injury or minor biomechanic fault.

Custom foot orthoses (CFO) are typically prescribed by a medical specialist and are created (fabricated) from model of an individual foot which has been balanced and modified to achieve a specific outcome. CFOs are typically an important part of a more extensive and comprehensive clinical plan of treatment for a previously diagnosed injury, biomechanic fault, anatomical/structural abnormality, and/or in an effort to alter the kinematics of running or cycling. The evidence supporting the clinical efficacy and benefits of these orthoses is growing.

The successful introduction of any foot orthoses should take into consideration the overall impact of the foot orthoses upon the athlete. This can be accomplished by examining the impact of the following constraints:

Dysfunctional properties of the foot to be supported,
Biomechanical properties of the foot,
Unique morphology of the foot,
The injury,
Pathomechanics of the injury,
Intended sport shoe, and
Intended sporting activity.

While the overall impact of one or more of these constraints may be dominant, considering each is critical to providing the most effective orthoses recommendation or prescription. When prescribing a CFO these constraints are most efficiently addressed by way of a *systematic approach* which integrates properties of the CFO with the athlete and injury. The prescription resulting from this approach would address

The need for a pathology-specific foot orthoses,
The creation of an accurate and functionally representative negative impression cast of the foot,
The importance of biomechanic-specific positive cast modifications,
An appropriate selection of orthoses shell construction materials,
The appropriate selection of rear post design, and
The contributing benefit of special additions, accommodations, extensions, and covering materials.

The resulting CFO would provide for the athlete the greatest potential for a device which is not only effective but also comfortable and well tolerated.

Pathology-specific foot orthoses have been shown to enhance the successful treatment of a variety of lower extremity injuries common to sporting activities. When implemented properly, the orthoses will diminish or counteract the occurrence of abnormal biomechanical forces which contribute to the injury of soft tissues, joints, and osseous structures during running and cycling. Thus the goal of pathology-specific foot orthoses is to identify the dysfunction of the foot relative to the injury and to direct specific device design characteristics to diminish the impact of the dysfunction upon the foot.

The creation of an accurate and functionally representative negative impression cast of the foot provides the first step leading to the fabrication of a CFO. While many techniques have been described this author prefers the suspension impression casting technique described by Root et al. This technique provides unique benefits not easily achieved by other commonly applied methods, such as ease of manipulation, intra-clinician cast consistency, ease of assessment for purposes of quality and casting position accuracy and ease of impression cast manipulation by orthoses making laboratories worldwide. While direct computer-based imaging technology has been available for a number of years its wide spread suitability for making of orthoses has been hampered by the proprietary nature of current imaging software, limited availability to the clinician, and the challenge to adequately miniaturize the imaging devices. However, any one of a number of modeling systems can achieve a satisfactory model of the foot from which to create a prescription foot orthoses as long as the clinician possesses the expertise and skills necessary to create a reliable and reproducible model of the human foot and recognizes the advantages and disadvantages of the modeling system being used.

Biomechanically specific positive cast modifications applied to CFOs can be categorized as either intrinsic or extrinsic in nature. Intrinsic cast modifications take place at the time the negative cast of the foot is “poured” to create a positive plaster model or scanned to create a positive computer model and typically includes balancing the bisection of the rearfoot to achieve an everted, perpendicular, inverted or Blake inverted positive model of the foot. Extrinsic cast modifications occur after a positive model of the foot has been rendered. These modifications generally are considered to include medial heel skive, cast fill, orthoses width, heel cup depth, fascial accommodations, and forefoot posting platform applications. The thoughtful combination of intrinsic and extrinsic positive cast modifications increases the potential that the resulting CFO will be effective.

Balancing of the impression cast at the time of “pouring” or scanning can impose a supinatory, pronatory, or neutral influence across the STJ and MTJ axis of rotation. When the posterior surface of the heel in the relaxed standing position is perpendicular and a mild or neutral supinatory influence is desired across the STJ and long axis of the MTJ a perpendicular or minor (2°–3°) inverted cast balance may be performed. While most orthoses making laboratories will default to a perpendicular balancing of the negative cast, many provide the opportunity to order other balancing positions. When the bisection of the posterior surface of the heel is everted in a relaxed standing position or when clear signs of heel eversion are noted during the late midstance or propulsive phases of gait are observed then an inverted balancing technique should be considered to increase the supinatory influence of the orthoses across the subtalar and midtarsal joint complexes. Up 6° can be tolerated; if a greater supinatory influence is required then a Blake inverted cast balancing technique should be considered. With this technique increased supinatory influence is directed across the subtalar joint. For every 5° of Blake inversion prescribed 1° of realized inverted positive cast position is achieved. Typical Blake inverted cast balancing for a triathlete would occur between 25° and 35° or a realized inverted influence of 5°–7°. Rarely would a clinician ever recommend an everted cast balance.

Kirby observed that the functional axis of rotation of the subtalar joint varied between individuals and he postulated that its anatomical location contributed significantly to the magnitude of the observed pronatory events effecting the foot. He theorized that by directing a force against the plantar medial surface of the heel the functional axis of rotation of the STJ would be shifted laterally, thereby augmenting the role of stance phase muscles such as the posterior tibial, gastrocsoleus, and flexor hallucis longus muscles to resupinate the foot. The resulting *medial heel skive technique or Kirby technique* was developed. Typically a 2–6 mm skiving of the plantar medial aspect of the heel is accomplished on the balanced positive cast. Increased skive results in an increased supinatory effect; typically a combination of inverted cast balance and medial heel skive is used to achieve the desired results. Caution should be taken when the triathlete exhibits atrophy of the medial calcaneal fat pad, a laterally displaced plantar fat pad, a prominent cicatrix, or a robust medial calcaneal tubercle spur.

Cast fill is a technique whereby the positive model of the foot can be "smoothed" to enhance comfort and performance without sacrifice to function. Potential areas of impingement including the medial arch and lateral column are overfilled smoothing transitions without altering contours. Typically cast fills are considered to be no fill, minimal fill, standard fill, and over fill. Use minimal fills to achieve the tightest contours. However, minimal fills will increase the risk of orthoses intolerance including excessive local pressure points, impingement, and even blister formation. Apply minimal fills when maximum influence of the orthoses is desired such as the hard to control foot or cavus foot. Use a standard fill when limited joint motion is suspected to arise out of osteoarthritis or when diminished sensation is present. A maximum fill, although rarely indicated, is useful when fitting an orthoses to a triathlete with chronic intrinsic muscle spasms, equinus, tarsal coalitions, midfoot fusions, or under any other circumstances where minimal orthoses influence can achieve symptomatic relief.

The distal balancing platform which extends across the forefoot is critical for support of the forefoot to rearfoot relationship. A "light fill" or "no fill" may be applied under circumstances where additional rigid support of the distal metatarsal phalangeal joints is desired. However, excessive light fill tends to lead to separation of the anterior edge of the CFO from the interior of the shoe. This can potentially be made worse by cycling shoes which possess a slightly concave medial to lateral profile.

Orthoses width traditionally has referred to the anterior width of the orthoses shell immediately proximal to the metatarsal phalangeal joints. A variety of widths can be selected depending upon the magnitude of influence the clinician desires from the orthoses shell. The widths include extra wide, full width, wide, standard, narrow, and extra narrow. For most triathletes wide, standard and narrow shells widths should be selected dependent on the injury and forefoot width of the running or cycling shoe. Many cycling shoes, however, will not accommodate a wide shell;

this author has increasingly prescribed a narrow or standard width shell with a medial flair. This effectively places greater orthoses surface area directly under the talonavicular, navicular medial cuneiform, and medial cuneiform articulations without compromising shoe fit. This technique is also beneficial when a wide or extra wide shell design restricts the natural plantar flexion of the medial column contributing to first metatarsal phalangeal joint dorsiflexion motion during the midstance and propulsive phases of running. This technique should also be considered when a tight or prominent central band of the plantar fascia is present.

New considerations for *heel cup depth* are now important as CFOs integrate heel skives and inverted balancing such as the Blake inverted. Shallow heel cups (12–14 mm) offer the advantage of ease of fitting into hard to fit shoes, especially cycling shoes or running shoes with narrow heel cups. While deep heel cups (18–24 mm) dramatically improve the surface contact area of the orthoses to the foot they also enhance rearfoot control critical to the application of various inverted balance techniques. Unfortunately, deep heel cups also increase the difficulty fitting an orthoses into shoes used by triathletes, especially cycling shoes. All heel cups require the application of an expansion, especially along the lateral and posterior lateral surfaces which serves to separate the foot from the orthoses shell minimizing the potential for heel soft tissue impingement such as edge irritation and blister formation. Herring and Green provide strong and compelling evidence that the expansion of heel soft tissues upon weight bearing can be accurately predicted from non-weight-bearing measurements. These authors measured the width of the heel under the conditions of non-weight bearing and weight bearing; reporting overall maximum and point of maximum heel soft tissue (heel fat pad) expansion for over 900 male and female individuals across a wide range of age classes. They observed that the point of maximum heel soft tissue expansion was individually specific and not directly linked circumstances such as gender, age, foot size, weight, or height, and this point of expansion occurs at a height which is well within the range used for deep heel cups (18–24 mm). Too little heel cup expansion risks soft tissue impingement while too much expansion imposes shoe fit difficulty. Herring and Green encourage clinicians prescribing CFOs to send non-weight-bearing or weight-bearing heel width measurements taken at the level of maximum heel expansion to avoid too little or too much heel cup expansion performed by the orthoses making laboratory.

Fascial accommodations allow the clinician to relieve the potential for irritation of the plantar fascia against the dorsal surface of the orthoses. Typically this represents an increased selective positive cast fill placed medial and lateral to the prominent margin of the plantar fascia and rising above the cast adequate to produce a channel in the resulting orthoses to accommodate the plantar fascia. This addition is especially important for athletes with a plantar fascia which becomes prominent during the propulsive phase of gait or when the plantar fascia exhibits fibrotic changes resulting from previous trauma. This addition will alter CFO longitudinal shell rigidity; through a “girder and beam effect” the introduction of a longitudinal trough designed into the dorsal surface of the CFO will increase resistance to longitudinal flexion of the resulting device under weight-bearing load. While this effect may be desirable in concept, it will be difficult to control and only promote a locally beneficial resistance to device deformation, influencing the medial aspect of the CFO more dramatically than the unaltered lateral surfaces.

Other accommodations may be added when prominent plantar anatomical features are present and would result in unnecessary pressure points during running and cycling. Typically, these additions accommodate a potentially sensitive plantar fibroma, a prominent styloid process of the fifth metatarsal or an accessory navicular. However, under conditions where a pressure dampening effect is sought in addition to accommodation the orthoses making laboratory may be asked to fill the accommodation on the device with a cushioned material to form a "sweet spot." This CFO addition should be designed in such a manner that size of the "sweet spot" is larger than the anatomical structure to be accommodated to avoid edge impingement during running and cycling activities. An application for this addition may be on the medial flare of the CFO to augment the support and cushioning of the talonavicular joint and related soft tissues.

A diverse array of materials are available for the fabrication of CFOs. The *selection of orthoses construction materials* is critical to the overall comfort, function, and performance of the CFO. For triathletes three general materials are frequently used for the construction of the typical CFO and include polypropylenes, graphites/fiberglass, and foams. However, under special circumstances other materials may be occasionally applied to the making of a CFO. While each of these materials offer the triathlete a unique assortment of advantages they also impose identifiable disadvantages that may out weight the advantages. Important similarities exist between each of the most frequently used materials including (1) a range of flexibility, (2) ease of initial molding, (3) resiliency of material, (4) ease of post-production modification, (5) durability under repeated and heavy use, and (6) availability of material making them more suitable for triathlete CFO devices. Foam materials are frequently used because of inherent cushioning properties and low weight to produce a CFO; however, the foams do not adapt well to post-production modifications and exhibit poor durability and require frequent replacement. However, with a wide selection of CFO materials, the clinician is able to better select the most suitable material of rigidity/flexibility of the finial device dependent upon the unique needs of the foot and the injury/pathology.

Polypropylene is the most universally applied material for running and cycling CFOs. This material is available in a variety of thicknesses and can provide the clinician with a wide range of flexibilities to select from especially if EVA arch fill is used to augment rigidity of the selected shell material. Dependent upon the degree of flexibility desired, select polypropylene thickness and EVA arch fill based upon the weight of the triathlete. The thinner polypropylene offers a greater degree of flexibility, while thicker polypropylene promotes greater rigidity. Intermediate levels of device flexibility can be achieved through the addition of an EVA arch or under fill. Further flexibility enhancements can be achieved by adjusting the firmness of the EVA material used to under fill the shell. Also influencing overall device flexibility is the manner in which the device is formed to the foot. CFOs that are heated and vacuum formed to a model of the foot are generally more flexible than a

CFO directly milled to the shape of the foot and of identical thickness. When polypropylene is heated it looses some of its natural rigidity.

Polypropylene has the distinct advantage that it can be molded easily to unusual shapes without wrinkling. This is of particular importance when considering the use of a balancing technique that will use a deep heel cup or when the shell must accommodate a prominent plantar protrusion (exostosis, prominent navicular tuberosity, a taught central band of the plantar aponeurosis, or fibroma). Once molded, polypropylene will retain its shape during repeated loading events; however, this material will eventually deteriorate, flattening, and loosening its initial functional control. Polypropylene's reduced resiliency is often described by some triathletes during running activities as a trend of greater perceived flexibility when directly compared to other more resilient (graphite and fiberglass composite) materials of similar flexibility.

Graphite materials have been used in the making of CFOs for more then 20 years. A variety of graphites are available including graphite acrylic laminates and composites. Graphite offers the distinct advantage of achieving functional support (semi-rigidity and rigidity) without excessive shell thickness minimizing bulk and weight. Graphite shell materials are also known for durability, longevity, high levels of resiliency, predictable flexibility through out the materials flexibility range, and mold ability. Similar to other shell materials graphite shells can be under filled to alter the flexibility properties of the raw material. Under filling a graphite shell with EVA should only be considered when the shell thickness desired is less than what would be optimal for the triathlete's weight or when the triathlete's weight exceeds even the most rigid materials. However, due to the risk of shell breakage, including hidden micro-fractures leading to orthoses failure, EVA under fills should be avoided and an alternate shell material such as polypropylene should be selected. Also when prescribing heel cup depths of greater than 18 mm, special attention must be applied to minimize wrinkling of the graphite around the narrower radius of curvature. This problem is being overcome as refinements to graphite shell technology has lead to ever thinner, stronger, and more resilient shells with increasingly better resistance to breakage and moldability, while maintaining consistent control throughout the flexibility range of the material. Increasingly graphite is becoming the shell material of choice for the triathlete desiring an orthoses of minimal bulk and weight with optimal durability, flexibility, and functional control.

Rearfoot orthoses posts promote no known functional benefit over the benefit already achieved by the orthoses shell. However, their continued use is done so with the intent to stabilize the foot orthoses in the shoe, especially during the heel contact and midstance phases of gait. Unfortunately no evidence has been provided to substantiate this hypothesis. A recent pilot study examined pressure (FScan) data generated by three subjects walking and explored their response to four rearfoot posting conditions (no post 0°, 4°, and 6° of motion). The results of this limited data concluded that posting the orthoses promoted no significant change to the subject's gait; however, a 0° rearfoot post did increase the duration of the heel contact phase of gait for each subject. These results would generally support the general hypothesis that rearfoot posts contribute little to the overall effect of the orthoses and at best can only serve to stabilize the orthoses in the shoe but only during the heel contact phase of gait. Thus, the basis for the use of a rearfoot post is done so more upon personal preferences and bias and not on functional outcome. However, the use of a 0° rearfoot post may influence heel contact phase stability adequately to permit a triathlete to use a less stable running shoe than might otherwise be recommended.

The finishing touches to any foot orthoses may include *special additions such as accommodations, extensions*, *and covering materials.* In fact, these additions are generally what the triathlete first encounters, evaluates, and scrutinizes; first impressions can be lasting and lead to a highly successful outcome or a disastrous conclusion. These additions should be selected based upon the characteristics of the foot and the specific pathology which is being treated by the foot orthoses. Numerous accommodations have been described and an endless array of special addition combinations could be described, each intended to suite a very specific application. Many special additions could be perceived as uncomfortable and counter productive when applied to the triathlete versus the general population. Several accommodations and special additions are of particular importance when considering the treatment of triathlon-related lower extremity injuries.

Extensions are additions that can extend the influence of an orthoses beyond the midstance phase of gait. These extensions can provide cushioning and/or promote a functional effect well into the propulsive and preswing phases of gait. The first most obvious role of an extension is to augment the natural cushioning properties of the forefoot and the cushioning of the properties of the shoe. An assortment of materials is available coming in a range of firmnesses and thicknesses. Avoid excessively thick cushioned extensions, while these will feel "pillow soft" walking they will also increase the energy demands placed upon the triathlete during running; select materials which are 1.5–3 mm (1/16–1/8″) thick.

An extension may be applied to the orthoses to influence forefoot function. Increasingly the function of the medial column and first ray has been suspected in the development of overuse injuries. During gait a stable first ray (first metatarsal and medial cuneiform) is a requirement for resupination of the foot and a propulsive gait pattern. When the first ray is unstable it will be dorsiflex until the metatarsocuneiform joint end point range of motion is achieved. "Locking" the first ray against the ground is important to minimize the development of functional hallux limitus and eccentric overload to the tibialis posterior, peroneal longus tendons, and the plantar aponeurosis. The application of a reverse Morton's extension to the foot orthoses will dramatically reduce the ground reactive force under the first metatarsophalangeal joint and reduce the potential of impact of functional hallux limitus. Varus extensions of 2°–4° can be applied to a foot orthoses to help relieve propulsive and preswing phase eccentric overload applied to the tibialis posterior muscle–tendon complex during running helping to reduce some of the symptoms associated with medial tibial stress syndrome (shin splints). When applying a varus forefoot wedge, a stable medial column is necessary since the introduction of the wedge will increase the ground reactive forces exerted to the first metatarsophalangeal joint complex. Valgus extensions of 2°–4° can be useful to reduce eccentric overload exerted upon the peroneal tendons. This extension can be applied in combination with a reverse Morton's extension to further enhance medial column stability, limiting functional hallux limitus, and augment peroneal longus functional role during the stance phase of gait. Clearly, a functional orthoses extension can extend the influence of the orthoses well into the propulsive and preswing phases of gait.

Accommodations applied to the orthoses shell can help to alleviate painful forefoot symptoms such as metatarsalgia, capsulitis and intermetatarsal neuritis, and Morton's neuroma. Locally applied metatarsal pads will serve to redistribute plantar forces from a symptomatic metatarsophalangeal joint or intermetatarsal space to less symptomatic adjacent structures. Generally these are applied proximal to the symptomatic joint of intermetatarsal space. Metatarsalgia is a common complaint of triathletes who log high mileage. The application of a soft poron metatarsal bar which extends across the distal one-third of the orthoses shell will serve to off-load the symptomatic metatarsophalangeal joints and spread ground reactive forces of running across the less symptomatic metatarsal shafts much like the application of a rocker bar to a shoe sole would accomplish. Finally, cutouts, apertures, and slots can be added to an extension to reduce ground reactive forces under specific metatarsophalangeal joints.

Accommodations built into the orthoses shell were discussed in the section discussing positive cast modifications. Accommodations such as "sweet spots" serve to reduce pressure and the potential for irritation across problematic anatomical sites such as navicular tuberosity, plantar fibroma, or a prominent central band of the plantar aponeurosis.

Covering materials may also vary and range from firm to soft cushioning. Vinyl, leather, soft EVA, and closed cell foam materials are the most common materials prescribed. Closed cell neylon or Spenco cushioned materials (Spenco Medical Corp. Waco, TX) offer the distinct advantage of providing cushioning as well as dissipating friction and torque which can contribute to friction blisters of the foot. These materials can also help to reduce the buildup of unwanted perspiration and moisture from around the foot further reducing the likelihood of friction blisters. Covering materials may be of various length, covering just the orthoses shell, or extending to the sulcus of the foot or out to the tips of the toes. Full-length top covers are better adapted and more comfortable for the triathlete.

When considering extension and top cover materials and pathology-specific needs carefully consider the shoe environment into which the foot orthoses will be fit. Over crowding the midfoot, forefoot, and/or toes can be as problematic and painful as the original complaint or problem. Cycling shoes will significantly limit the accumulative thickness of accommodations, extensions, and top covers. Running shoes on the other hand will be far more forgiving to these additions.

By focusing orthoses treatment and design upon the specific pathology needs of the triathlete and by avoiding treatment driven by a deformity orthoses outcome will be improved. Furthermore, an understanding of the triathlete's pathomechanics leading to the symptoms and injury, running gait, and cycling pattern will permit the design and development of orthoses that best meet the needs of the triathlete and symptomatic pathology. Unfortunately, there are no clear-cut rules that can guide the clinician to the development of the most effective foot orthoses and clearly multiple and different orthoses models may provide the desired outcome of reduced symptoms. Thus by approaching the development of an orthoses in a systematic step wise manner will dramatically reduce the likelihood of orthoses failure.

The Athlete and Overuse Injuries

The triathlete comes in all shapes and sizes, from lightweight runners to over 200-lb. Clydesdales of both genders and most age classes. Overuse injuries are the most common injuries confronting the triathlete during the long hours of demanding training and racing. Structural abnormalities, poor strength and range of motion, poor overall conditioning, improper training plans, old and worn out equipment, and poorly adjusted/fit equipment are some of the most common causes leading up to the development of an overuse injury. However, with so many new and inexperienced endurance athletes joining the ranks of triathletes old long forgotten and dormant injuries of work, sports, and recreation can be triggered or contribute to the development a new injury. Each of the sporting components associated with triathlons and duathlons exposes the athlete to a unique physical stress and can lead to a unique group of overuse injuries. Many of these overuse injuries can be prevented and/or treated in part through the careful selection and application of foot orthoses and shoes.

Running typically exposes the triathlete to many hours of pounding out long slow distance miles on pavement. As conditioning improves so might the demands of training as the triathlete begins to add strength and interval training to their training program. Numerous overuse injuries can be associated with running including those shown in Table 16.1 Each of these injuries can be linked to abnormal

Table 16.1 Overuse injuries associated with running

Low back pain
Iliotibial band syndrome
Patellofemoral pain syndrome (inferior and medial)
Medial tibial stress syndrome (shin splints)
Achilles tendinitis, bursitis, and enthesitis
Tibialis posterior tendinitis
Tibialis anterior tendinitis
Peroneal longus and/or brevis tendonitis
Flexor hallucis tendinitis
Spring ligament strain
Plantar fasciitis
Baxter's nerve entrapment
Metatarsalgia
Capsulitis
Sesamoiditis
Intermetatarsal neuritis and Morton's neuroma
Stress fractures (tibia, fibula, navicular, and metatarsals)
Friction blisters and subungual hematomas (black toenails)

Table 16.2 Overuse injuries common in cycling

Low back pain
Patellofemoral pain syndrome
Iliotibial band syndrome
Calf cramping
Medial malleolar contusions
Achilles tendinitis, bursitis, and enthesitis
Peroneal tendinitis
Intermetatarsal neuritis/Morton's neuroma
Metatarsalgia
Capsulitis
Sesamoiditis
Bursitis (fifth MTPJ)
Stress fractures (tibia, fibula, navicular, and metatarsals)
Friction blisters and subungual hematomas (black toenails)

pathomechanics of the lower extremity and can respond complete or in part to the introduction of proper shoes and foot orthoses.

Cycling exposes the triathlete to the stress of long hours of spinning at high cycling cadences for long hours. Climbing and the effort to spin in big gears increase the stresses exerted upon the soft tissues and joints of the lower extremity leading to the potential for overuse injuries such as those shown in Table 16.2 These cycling injuries as with many overuse injuries of the lower extremity can respond favorably to the introduction of foot orthoses, careful selection cycling shoes, and pedal/cleat system.

The Older-Aged Triathlete

Increasing age influences the musculoskeletal and kinematic response to the running and cycling phases of triathlon racing and training. During the running phase, variations to the stance phase of gait may occur with increasing age. The older-aged runner (55 years and older) may exhibit degenerative musculoskeletal changes that influence ground reaction forces and kinematics during distance running. Older runners frequently experiences loss of lower extremity joint flexibility and ranges of motion, progressive weakness to muscle and bone, diminished vascular supply to many lower extremity connective tissues, atrophy, and loss of elasticity to numerous lower extremity connective tissue structures such as the plantar fat pad, plantar aponeurosis, and Achilles tendon and frequently the loss of strength and contractile velocity of major lower extremity muscle complexes. These changes frequently contribute to an altered running gait. Older runners exhibit a shorter stride length with a higher cadence, smaller knee ranges of motion, higher vertical impact speeds, higher impact peak forces, and higher initial loading rates than their younger running peers. Intrinsic shock absorbing capabilities of the lower extremity are also compromised with increased age as elasticity of connective tissues is lost.

The cycling phase of triathlon racing and training does not appear to influence the older-aged triathlete with the same magnitude as that experienced during the running phase of racing and training. However, the cycling phase of training and racing may also adversely effect the older triathlete. As observed to the running phase, the aging triathlete is more susceptible to the development overuse injuries; these injuries can be linked to the loss of lower extremity joint flexibility, progressive muscle weakness, and loss of elasticity of connective tissues including tendons, ligaments, and articular cartilage.

While these changes are representative of normal aging they may also provide an explanation for the higher incidence of overuse injuries associated with running and for the potential that similar circumstances may influence the older-aged triathlete. Given these factors and the demands of multisport training the older-aged triathlete may require special attention to intrinsic factors such as range of motion and strength training as well as extrinsic factors such as equipment (gearing, cranks, pedals, shoes, and foot orthoses), bike-fit properties, and training modifications in and effort to reduce even minor yet abnormal musculoskeletal and joint stress.

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Footwear and Cross-Training

17

Amol Saxena

Injured athletes will need proper shoe gear even when cross-training. Typically, they may use their usual sports-specific footwear; however, this may not be ideal. It is an area that has not been thoroughly researched, so this chapter will only serve as a guideline.

Use of the pool for cross-training is popular, but often no mention is made of shoe gear. For example, some athletes will need footwear when running on an underwater treadmill or in the shallow end. These shoes tend to be lighter and allow for drainage (Fig. 17.1). When exercising in the deep-end of a pool, shoe gear may not be required. However, there are some shoes designed to provide resistance (Fig. 17.2).

Newer types of cross-training equipment may require other shoe considerations. For example, on a typical treadmill, one often places the running surface at a 1–2% incline to compensate for the lack of wind resistance. On an AlterG™ (Fremont, CA, USA) treadmill, where one runs at less than full bodyweight, especially less than 85% of body weight, the runner will strike more on the forefoot [1] (Fig. 17.3). This may require more forefoot padding in the shoe, and cause faster forefoot shoe wear. On elliptical trainers, conversely, the shoe may need to be thinner under the forefoot so there is less vertical displacement (Fig. 17.4).

Other types of cross-training, such as cycling, should consider sports-specific shoe gear, i.e., cycling shoes with specific pedal/cleat interface. Foot mechanics are not the same as running gait. Therefore, if a patient needs biomechanical adjustment, this should be taken into account, via wedges between the cleat and shoe or an in-shoe cycling orthosis if room allows, with a forefoot varus extension (Fig. 17.5). More detail on this can be found in the cycling and triathlon chapters.

Certain injuries and pathologies require footwear choice considerations. For example, patients may have Hallux Rigidus, and cross-country skiing may aggravate

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Fig. 17.1 Shoe for pool running in shallow end or underwater treadmill

Fig. 17.2 Shoe designed for pool running

the condition. Skate-style boots may be better as opposed to in-line skate boots. Also, when doing push-ups or planks, a stiffer shoe with a rocker sole, as opposed to barefoot, would be beneficial for those with forefoot problems (Fig. 17.6).

Just as one should consider a sport-specific shoe, the cross-training activity and the current pathology should be assessed. Recognizing which activity and stresses that can occur is paramount. The cross-training should not create, aggravate, nor cause additional injury.

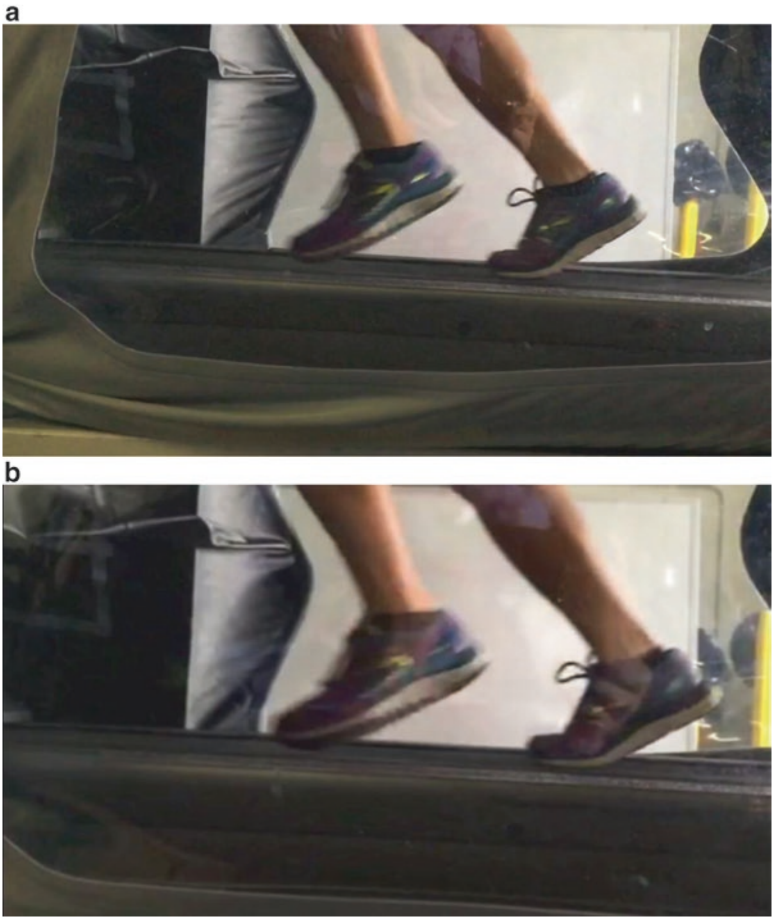

Fig. 17.3 Runner in AlterG™ running @ 70% bodyweight landing more on forefoot

Fig. 17.4 Shoe on an Ellipitigo™

Fig. 17.5 Cycling shoe with wedges

Fig. 17.6 Shoe with rocker sole, which can alleviate forefoot pain by decreasing hyperextension when doing exercises such as push-ups or planks

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Racing Track and Cross-Country

18

Brian W. Fullem

Serious runners often use a lighter shoe when running a race. The shoe are commonly referred to as racing flats and are used for road racing or cross-country races that involves some harder surfaces. Spikes are commonly worn for track and field and cross-country races without road as part of the course. The hallmark of these shoes is that they are much lighter and less supportive than everyday training shoes. Athletes do not need all the support and cushioning when running a race less than a ½ marathon. It is advisable for athletes to use these shoes during some training sessions prior to racing, and a speed workout lends itself well to testing racing flats prior to competition. If the transition to racing shoes and spikes is sudden, then injuries may result, particularly calf soreness and pain secondary to going from wearing a training shoe with a heel height to forefoot ratio of 8–12 mm to a negative heel height ratio such as in a sprint spike. It is sometimes advisable for athletes to wear a lightweight training shoe or road racing flat for a longer race instead of a spike if one is returning from an injury or in a non-championship race. Additionally adding any type of arch support can be a challenge in these low volume shoes, a thin graphite composite can work well if a custom device is required and dress type over the counter devices are my first line of treatment when necessary.

There is some evidence in the medical literature that lighter shoes may lead to better running economy and therefore improved performance, even a minimal advantage can be important to someone trying to set a personal best.

Cheung et al. [1] performed a meta-analysis published in March 2015, in which 13 studies with 168 total runners were found to have an improvement in running economy in lighter shoes as well as when barefoot. Fuller et al. [2] reviewed studies as well in March 2015 and concluded that runners had better economy using lighter

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shoes and shoes over 440 g are detrimental to economy, which should translate to worse performance.

Track Spikes

The first track spikes (Fig. 18.1) were created by JW Foster in 1895, the company would later became Reebok.

Track spikes for running events are typically composed of a thin layer of mid-sole protection which becomes thicker as the event becomes longer. In a distance spike (Fig. 18.2) the distal 1/3 of the shoe is composed of the spike plate, often composed of a plastic or other lightweight composite material with removable

Fig. 18.1 The Foster's Running Pumps depicted are from 1924. Photo from http://retrobok.com/2012/03/27/first-reebok-shoes/

Fig. 18.2 (**a**, **b**) Distance spike

elements. Most track facilities require the elements be ¼″ or less. Occasionally these elements could be in an area of a boney prominence such as under a metatarsal head or the sesamoids and that particular spike element may need to be removed. Any examination of an athlete should include ALL of the shoes that are used including racing, training, and casual.

Whereas a sprint spike (Fig. 18.3) will often have a full length spike plate to provide a greater lever arm since midshole cushioning is not necessary because foot strike will be in the forefoot. Notice that the sprint spike is curved at the end similar to a rocker bottom shoe to assist propulsion as well.

A cross-country spike (Fig. 18.4) will often have rubber protrusions similar to spikes to help with traction and in cases of muddy courses up to 5/8″ spike elements are routinely employed. The importance of the proper choice of spike cannot be underestimated. In the 1983 New York State High School Cross Country championships, the

Fig. 18.3 (**a**, **b**) Sprint spike, note the plastic type foot plate extends over the entire device

Fig. 18.4 (**a**, **b**) Cross-country spike

Fig. 18.5 (**a**) High jump on the left; (**b**) javelin

Fig. 18.6 (**a**) Asics Gel Hyperspeed comes in at 4.5 oz./128 g. (**b**) Men's Brooks T7 weighs just under 6 oz. at 170 g

team that was the overwhelming favorite to win the title finished second on a muddy course due in part to not having spikes, they only brought racing flats.

For field event athletes the spikes will sometimes be placed in the heel as well. There are special demands placed on the body during these events and the torque produced requires the spikes to be placed in the rearfoot to help stabilize the foot at take off in the high jump (Fig. 18.5a) and at release in the javelin (Fig. 18.5b). High jumpers will also sometimes wear two different types of spikes.

Racing flats (Fig. 18.6a, b) are commonly employed for road races, cross-country courses that are not exclusively on soft surfaces and some longer track races such as the 10,000 m. Racing flats appear to be stripped down versions of training shoes without any motion control properties. A premium is placed on being lightweight and some shoes are designed with more midsole protection. For example, the women's Asics Gel Hyperspeed comes in at 4.5 oz./128 g and the men's Brooks T7 weighs just under 6 oz. at 170 g

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Specialty Running Stores and the Sports Medicine Professional: A Natural Partnership

19

Rich Wills

Sports medicine professionals can count on specialty running stores to provide sound footwear advice and solutions for their patients. They can also expect that their recommendations to see a specialty running store for appropriate footwear will benefit not just their patients, but their practices as well because specialty running stores typically provide a higher level of expertise and concern for the patient than any other retail source. Ultimately, this reflects well on the referring medical professional and produces optimal footwear recommendations for the patients.

Specialty running stores serve as an important resource for sports medicine professionals. These stores, by the nature of the fitting processes they employ with customers, can provide reliable guidance in the key area of footwear selection for the patients of sports medicine professionals.

Over 1000 specialty running stores exist throughout the country, and the Running Industry Association (formerly the Independent Running Retailers Association, or IRRA) is the guiding body for the majority of them. Founded in the early 2000s, the Running Industry Association's (RIA) mission is to help specialty running stores cultivate excellence in (1) store education, (2) communication, (3) research, and (4) advocacy. This is important for sports medicine professionals because matching patients with footwear that is appropriate for both their biomechanics and their medical issues can have significant effects on the efficacy of their treatments once they are outside the medical setting, and no other retail channel or source is more educated or better equipped to provide that guidance to patients.

(1) Specialty running stores are sit-and-fit environments where customers are usually educated on, not just the products, but their own biomechanics and how the products will interact with and affect their biomechanics. Nowhere else can customers regularly expect to find knowledgeable staff who know how to fit highly

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engineered shoes to their unique gaits and other issues—issues like the types of injuries that sports medicine professionals are often treating them for.

The RIA's mission speaks to the importance of *education* in the channel precisely because customers and patients benefit so much from appropriate guidance in selection of their footwear, as it helps to keep them more injury resistant and to recover more quickly from injuries. The RIA promotes and puts on a variety of continuing education opportunities for members throughout the country and throughout the year. Attendance at these events is high, as member stores recognize the importance of being as educated in the field as possible. It benefits their customers (your patients) and their profitability when they establish themselves as sources of knowledge and guidance, as well as actual footwear products.

A referral to a good specialty running store for footwear advice can be seen as continuation of the medical professional's treatment and will usually result in favorable impression of both the medical professional and the store being made on the patient. Most importantly, it often benefits the patient in their recovery or treatment and beyond.

(2) Being able to effectively *communicate* with customers and patients is crucial to the transmission of the knowledge and education discussed above. Sports medicine professionals can be confident that knowledge, not fads, are being promoted in most specialty running stores, especially those associated with the Running Industry Association, and that customers and patients are being educated with information that is both credible and grounded in science.

It is also important to note that most specialty running stores see themselves as serving the medical professionals who refer patients to them. While store employees will often provide layman's knowledge and even treatment suggestions about typical running- and walking-related injuries like plantar fasciitis, shin splints, etc., they usually acknowledge that (1) information provided by the store is not diagnostic and that only trained medical professionals can diagnose and give official treatment suggestions for patients' particular conditions and (2) when medical professionals are involved, specialty running stores defer to them for actual diagnosis and treatment suggestions, and even footwear fitting suggestions if the medical professional has made a recommendation.

Specialty running stores also direct many of their customers to sports medicine professionals in their areas, so becoming acquainted with the local store(s) and store personnel can become a source of referral for the sports medicine practitioner, as well. Referrals between sports medicine professionals and specialty running stores often develop into very busy two-way streets!

(3) Perhaps the most important role that specialty running stores serve for sports medicine professionals is that of a *laboratory* for footwear products and best practices for runners and walkers. New brands, emerging technologies and nascent theories on training practices, injury prevention and biomechanics often find fertile ground for exploration in specialty running stores precisely because the staff and ownership are usually so well educated and experienced in the field. Trends are validated (or not) and fads are more quickly exposed in specialty running stores than anywhere else in the retail world. The experience, often decades long, of most

specialty running stores helps them make sure that customers and patients don't just dive off the deep end in pursuit of the latest magazine, celebrity or brand-driven craze. Customers and patients are guided, based on the years of practical in-the-field experience and the continuing education of the staff at most specialty running stores.

As mentioned above, however, many customers are also guided by the direction of the local medical professionals. Specialty running stores typically cultivate close relationships with sports medicine professionals in their area and usually listen attentively to the guidance and recommendations of the medical professionals, especially as it pertains to their patients.

(4) Specialty running stores are also *advocates*, first and foremost, for their customers. Helping customers (and patients of referring medical professionals) succeed is a key component of the DNA of just about every successful running store in the market. The specialty running store business model works best, almost without exception, when the interests of the customers and patients are kept a priority.

As you can see, sports medicine professionals and running specialty stores are natural partners. When it comes to obtaining appropriate footwear, sports medicine professionals can be confident that the interests of their patients are better prioritized by local specialty running stores than in any other retail space. Sports medicine professionals should also be confident that specialty running stores will serve their patients with credible knowledge in ways that are both a positive reflection of and even an extension of the referring sports medicine professional's practice.

Part III

Sport-Specific Athletic Footwear and Orthoses

Golf

20

Jonathan Blum

Twenty-nine million people in the United States alone and 55 million people worldwide play the sport of golf. Its popularity is partly due to playing in a sociable, natural environment and combining the health benefits of walking that can reduce stress and improve cardiovascular health. Golf also can be played by a wide variety of ages and skill levels. Handicaps are developed over time and represent a number of strokes a player will make over the course of a round. The lower the handicap a player has, the better the player. Golf is both a sport of distance and accuracy. Distance is enhanced by greater stability, and accuracy is associated with greater stability and lesser mobility [1].

The golf footwear market has been rapidly evolving. Technological and research-based advancements are providing shoe companies the means to develop lighter, more stable, fashion forward shoes. This chapter seeks to evaluate kinematics of swing and its relationship to footwear choices.

Biomechanical Lower Extremity Demands of a Golf Swing

Golf involves two activities walking and swinging. Footwear demands for both activities may not be fully compatible [2, 3]. Walking during a round can extend 4–5 miles over varying terrains. The act of swinging is a highly coordinated, multi-level motion that has tremendous variability amongst players. The ideal swing is made up of a solid stance, posture, and grip. Good foot action is considered the hallmark of an accomplished golfer [4]. Golf is not a reactionary game, yet the swing is considered one of the most difficult biomechanical sporting motions to execute.

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Fig. 20.1 Four phases of swing: (*1*) address, (*2*) backswing, (*3*) downswing, (*4*) contact/follow through

Swing can be divided into four phases: address, backswing, downswing, and contact/follow through (Fig. 20.1). Throughout each phase the front and back feet perform very different functions [3]. These functions have been studied with the intent on improving golf footwear design.

Address

The beginning of the swing starts here with the proper posture. Weight should be evenly distributed between both feet with a slight increase in pressure on the forefoot and on the insides of both feet. Depending on the club used and the length of the swing, determines the width of stance. The longer the club and swing, then the wider the stance. Middle irons generally call for the feet to be shoulder width apart. Correct width of stance ensures one can create a turn without restricting one's pelvic rotation [5]. A stable address can be considered the beginning building block in creating club-head velocity.

Backswing

The purpose of backswing is to provide for an efficient yet powerful downswing. This requires a stable body core, proper foot alignment, and aligned club-head [6]. Backswing is initiated when the front foot starts to unload with a laterally to medially directed force. During early backswing, weight is shifted to the back foot that is evenly distributed. As backswing progresses, lateral forces increase on the back foot, creating more momentum on downswing. However, excessive weight shift laterally leaves a player unstable resulting in sway. Sway will result in a decrease in power and poor ball striking. Simultaneously, the forces shift from anterior to posterior in the front foot and posterior to anterior in the back foot [2]. This can result in the front foot heel potentially coming up, which is acceptable to allow for a full shoulder turn. The average shoulder rotation (78°–102°) is approximately 2× hip rotation (47°–55°). Overall, in elite players the backswing has been found to be 0.82 s [6, 7].

Downswing

Downswing brings a rapid shift of weight laterally directed from the back foot to the front foot. The back foot is the "driver" here which accelerates the body's center of mass to the front foot [3]. As weight shifts laterally, it unloads the back foot, leaving a medially placed stress on the hallux and first MPJ of the back foot. The momentum also brings down the heel of the front foot. This reestablishes a supporting position, similar to the front foot at address, to allow for the upcoming unwinding and contact. Ultimately, both feet perform a turning moment crucial to downswing [3]. The centrifugal forces here have been measured at 1.6× body weight [3, 8]. The now increasing ground reactive forces, with an optimum weight transfer from back to front foot, will increase club-head velocity. Therefore, the shoe/ground interface is a vital link to performance of the swing [6, 9].

Contact and Follow Through

From the ground up the swing is unwinding. The front foot is now similar to the address phase in terms of position and weighting and stable at contact, established without unwinding the upper body and storing the energy to be laterally directed toward the target. At impact the hips are now open 2–3× the shoulders. Max torque is now doubled on the front versus the back foot with up to 80% of body weight on the front leg [6, 9, 10]. As the swing continues, it decelerates with pressure finishing on the outside and heel of the front foot and increasing onto the hallux and first MPJ of the back foot with upward pressure almost lifting the player off the ground. At finish of follow through the player should be upright, facing the target and well balanced.

Anatomy of a Golf Shoe

Upper Materials

In golf the upper materials need to provide support, stability, ventilation, and lend waterproof properties. The quality, feel, and now appearance of the material influence overall shoe comfort, function, and desirability. The most popular material is full grain leather. After processing it is added to the exterior of the shoe creating a stretch-free and form fitting waterproof shoe. Leather uppers are generally more expensive but breathe well and are best suited for warmer play. Synthetic nonporous polyester uppers are a less expensive option to leather. It is spread over the shoe and is lighter and thinner than leather but less breathable. Manufacturers now have alternatives in sock lining. The most popular is Gortex®, a thick, water resistant material, excellent in cooler climates. Conversely, Outlast, originally developed by NASA to regulate the temperature of space suits, is now employed by Puma's Titan Tour shoe. It uses phase changing materials that absorb heat from inside the shoe, regulating heat and comfort. The lasting margin of the upper is attached onto the last which is responsible for the basic fit of the shoe. The most common lasting is a wider forefoot, standard midfoot, and slightly narrower heel. The wide forefoot allows for comfort, freedom of motion, and easier balance supporting swing mechanics.

Outsole

The outsole material comes in direct contact with the ground. Golf shoe outsoles are designed wider than traditional athletic shoes to provide stability, traction, and durability versus designed for mobility. They are manufactured from leather, nylon, and now more commonly TPU or vulcanized rubber. Spikes are strategically placed on the outsole to improve traction and are either molded as a one piece construction or with spikes that are removable and attached by different methods to the outsole. The traditional dress heel on outsoles are made to go along with the natural motion of swing. But more commonly today, there is a shift toward a sports wedge with midsole design.

Midsole

The midsole of a golf shoe provides shock absorption but also is important in supporting lateral movement and stability. Traditional materials include polyurethane, various rubber compounds, and EVA. Manufacturers are now borrowing technologies from athletic shoes to create more comfort and to decrease the weight of the shoe. Utilizing a lighter weight shoe, over the course of 4–5 miles walked, will markedly decrease leg fatigue during a round of golf.

Spikes/Cleats

As golf has increased in popularity so has the damage to golf courses specifically putting greens. This is believed to be due to the traditional 6–8 mm metal spikes that compact the soil preventing and weakening deep root formation. The spikes then compress and grip the grass roots leaving turf damage [11, 12]. This has led to the ban on metal spikes at golf courses and the creation of alternative spike and molded designs. Alternative spikes are also commonly referred to as cleats or spikeless. On golf shoes, the alternative spikes are shorter than on football or soccer cleats. They

Fig. 20.2 BOA closure system

are designed to allow for the motion of the swing versus for running. To counteract the depth penetration of only 1–3 mm into the turf, the contact area is made wider with multiple legs or swirls incorporating sole moldings between spikes [13]. Many options are available but commonly seen are six or nine alternative spikes strategically placed. Rubber soled "street shoes" have studs, bars, or nubs in place of golf spikes. Essentially designed for style and comfort, the trade-off can be less grip and stability on the course.

Lacing

Golf shoe lacing is dominated by traditional athletic footwear closure. Velcro closures are easy to use but seen infrequently due to the lack of stability transferred to the upper, slippage, and their overall style. Velcro is reserved mostly for golfing sandals. New proprietary systems, such as the BOA closure system, are entering the marketplace (Fig. 20.2). The BOA closure system consists of steel lace, nylon guides, and a mechanical reel. With the turn of a knob, shoe fit can be "dialed in" for a glove-like fit. The system claims improved comfort, lighter weight, faster operation on the fly, and cleaner looks.

How to Fit

Golf shoes should fit well, feel comfortable, and offer considerable support (see Table 20.1). Due to the supportive nature of golf shoes, they should fit more snugly than an average pair of shoes. However, if the width is too small, besides being painful over a round of golf, the foot is unable to spread out creating instability. The poorly fitting shoes will also wear out faster and provide less support and cushioning affecting swing mechanics [14]. Conversely, if the shoes are too big, the feet will slide during swing, losing traction and also affecting the swing.

Table 20.1 Ten fitting tips

• Measure both feet with a Brannock Device, if different use longer size
• Wear socks you will play golf in when trying on new shoes
• There should be 1/2″ space between longest toe to the end of the shoe when standing
• Choose shoes based on foot type. Pronated feet need shoes considered firm cushioning and semiflexible, supinated feet need cushioned shoes with stable flexibility, neutral feet have more choices but should steer toward the best-constructed shoes
• Width and length must be considered for fitting; width disparities are usually of greater importance for stability
• To check if too wide, when bending the forefoot if too much bunching or breaking of the leather likely too wide as foot not filling volume of the shoe. Another test is to take the insole/liner out and stand on it to check width if unsure
• If top eyelets touch after tying laces, shoe is too wide
• Eyelets greater than 5/8″ apart, indicate that the shoe is too narrow
• Should be no slippage in the heel
• Shoes should be comfortable when buying

Current Designs

Historically, golf shoes were wingtip oxfords with spikes. They offered water resistance and stability due to the metal spike's grip and a more stable upper. Oxfords weighed approximately 32 oz. Shoes generally now weigh 50% less, thanks to the availability of multiple high-tech lightweight materials. The reduction in weight provides less fatigue on the legs during a round of golf. This has been one of the biggest differences in the last 10–15 years.

For years golfers had to compromise comfort for performance; the more rigid, the more stable. Not anymore as designers are borrowing technologies found in cleated-shoe sports like soccer and baseball, and non-cleated ones like skateboarding and wrestling, to create footwear that offers the ideal combination of stability, traction, and even comfort [15]. Currently, golf shoes fall into one of three main categories: spikeless, classic, or athletic. Selecting the correct shoe is important to help optimize one's swing.

Spikeless or Street Style Shoes

Spikeless, or street style shoes, are generally the lightest weight 12–15 oz. They have no removable cleats but have a consistent pattern of ridges, lugs, or nubs on the entire sole. They are styled more like sneakers with extra cushioning in the midfoot/insole (Fig. 20.3). Fred Couples popularized them by wearing a pair of Ecco Streets Premiers at the Master's in 2010.

According to Golf Datatech a Kissimmee, FL-based tracking firm, street style shoes in 2012 accounted for 12.7% of all golf shoes sold. That is, a 125% increase

Fig. 20.3 Street styles shoes have many nubs on the entire sole making them very versatile on and off the golf course

Fig. 20.4 Classic golf shoes replicate traditional dress shoes with more cleats than other styles of golf shoes

from the prior year and with hybrid shoes expected to be 40%–50% of all golf shoes [16]. This current trend in golf shoes is driven by comfort and style. Today's golfer loves the versatility to be able to wear them on and off the golf course. However, only 5% of PGA golfers wear the style. Versatility in a shoe is not as important as traction and weight to professional golfers, as they spend 8–12 hours a day or 30–40 hours a week in their shoes. Making shoe selection is as important as choosing clubs.

Classic Golf Shoes

This style golf shoe weighs the most at 16–32 oz. The soles are flatter and leather with minimal traction elements but have more cleats than the other two categories. They have nine to eleven cleats with four on the heel and are dress shoe style, saddle or blucher with full grain leather uppers (Fig. 20.4). This shoe style may be ideal to create a seamless transition for a daily dress shoe wearer at work with a more structured shoe on the golf course.

Fig. 20.5 Replaceable plastic cleats of athletic style golf shoes offer greater amounts of traction

Athletic Golf Shoes

Athletic golf shoes weigh between 14 and 18 oz. The soles are molded from TPU with flexible midsoles. They will have less cleats in the range of seven to nine. These cleats can be changed out when they have become worn out as opposed to street style shoes which will need to be completely replaced. In addition to the cleats, the soles will have multiple traction points, either ridges, lugs, swirls, or bars often greater than 100 in number. Stability of the sole is augmented by a wider width in the forefoot (Fig. 20.5) [17].

Alternative Footwear

Less traditional footwear including golf sandals, golf boots, and minimalist shoes are available today (Fig. 20.6). These styles are generally not as popular with the masses; each has their own form of benefit. Golf sandals offer the golfer a shoe that stays cool and breathes well in hot weather. However, they can be uncomfortable with extensive walking putting the wearer at risk for blisters due to the straps, while also offering less lateral support. Golf boots are designed to look like hiking boots offering cleats on the sole with significant waterproofing for increased traction and warmth in winter months. The boots are heavier than other styles and do not allow for as much freedom in the ankles during swing.

The current minimalist trend has also been introduced into golf shoes. Minimalist golf shoes are flexible and intend to harness the natural motion of the feet. Design features of this style are a lightweight shoe that weighs 10–14 oz. It is built upon a zero drop platform of a thin 8–10 mm outsole with no midsole. The zero drop thin soles attempt to keep the golfer in contact with the ground longer, increasing posture and stability from the ground up. Following minimalist philosophy, a wide toe permits the toes to spread out and allows small muscle activation in the feet creating increases in stability and proprioceptive feedback. Currently, there is no literature to unequivocally support minimalist technologies.

Fig. 20.6 (**a**) Golf sandals, (**b**) Minimalist golf shoes, (**c**) Golf boots

Orthotics

Orthotics in golf can help promote proper alignment and stability of both feet. Prefab and custom orthotics are available. Prefab orthotics may not be the best for all golfers, not only due to fit but also due to the asymmetrical function of the feet during swing [3, 18, 20, 21]. Other than endorsements and anecdotal information, there is not a lot of scientific data to support most prefab orthotics for improving performance or for treating and/or minimizing golf injuries [19]. Custom orthotics will promote greater efficiency during swing. Improved foot function improves balance influencing the closed kinetic chain and thus increasing club-head velocity. Stude and Gullickson's study in 2000 with custom orthotics found a 3–5 mph increase in club-head velocity or a relative increase of 7% [20]. It has been determined that an increase of 1 mph in club-head velocity translates into an increase of three yards in air travel distance [20]. Additional studies with custom orthotics have found them to not only enhance balance and proprioception but also reduce the effects of fatigue and improve the likelihood of more consistent performance and ballstriking [5, 21]. At their optimum, well-constructed custom orthotics will reduce postural sway, decrease predisposition to injury, improve accuracy and distance, and maintain the spine angle resulting in less swing faults.

Shoe Performance

Due to mandatory changes in golf shoe spike requirements, concerns have been raised in regard to slippage and performance of newer golf shoe designs. Studies comparing metal to alternative spike and alternative spike to street style shoes have addressed the concerns. Metal spikes provide more forefoot linear (7%) and rotational traction (31%). Also seen are greater complete foot inward (11%) and outward (18%) rotatory traction. But complete foot linear traction for both metal and alternative were the same. This suggests that when only the forefoot was in contact with the grass, the additional moldings on the forefoot with alternative spikes was not enough to fully compensate for the decrease in depth of penetration [22]. In terms of maximal force, force generation, and coefficient of friction measures, alternative and metal spike shoes produced similar forces. Therefore, alternative spikes would not place the golfer at risk for slippage possibly resulting in loss of momentum transferred to the ball or predisposition to injury [12, 23]. Comparison of alternative spike design to street style shoes has been performed at the Soft Spikes Advanced Research Center. Alternative spikes provided 70% more traction in wet conditions and holding 32% longer than cleatless. In dry conditions, alternative spikes provided 51% more traction and holding traction 34% longer than cleatless. After 20 rounds of golf, alternative spikes maintained 100% of original traction in wet and 94% in dry conditions. Cleatless designs lost 26–28% traction in both wet and dry conditions.

Common Injuries and Treatments

Acute injuries in golf are not common and are usually due to a slip or trip over something, resulting in inversion injuries. Chronic injuries in professional golfers are attributed to overuse or increase in play, while in amateur golfers are due to incorrect swings, poor biomechanics, or improperly fitting shoes exacerbating underlying conditions. Overall due to the noncontact nature of golf over 80% of injuries are due to overuse. The risk of injury to a golfer increases for those who play more than four rounds of golf or hit more than 200 range balls or more a week. Those who carry their golf bag will increase back, shoulder, and ankle conditions. For all golfers the average time lost to foot and ankle injuries is 55.2 days [24]. Foot and/or ankle injuries amongst pro/amateur, male/female golfers account for anywhere from 1.4% to 12.9% of all golfing injuries [24–27]. However, warm-up routines of at least 10 min had positive effects on injury prevention [25].

Ankle Sprains

Ankle sprains occur due to an inversion injury to the ankle. During golf this can happen while walking, swinging on the uneven terrain of a golf course, and possibly from the transmitted force of the swing itself. Treatment for acute injury includes splint/immobilization, ice, compression, and rest. The acute phase is to be followed by a course of functional rehabilitation. The focus of rehabilitation needs to be on strengthening of the peroneals, increasing proprioception, and decreasing edema. Chronic instability can be treated with bracing or custom orthotics with a neutral posted heel and starting with 1/8″ increments of korex valgus wedge forefoot.

Achilles Tendonitis

This can be a result of prolonged walking particularly on uneven terrain and uphill lies, lack of warm-up, repetitive eccentric overload, or improper shoe choices. Early treatments should consist of refraining from golfing activity, ice, stretching program, NSAIDS, heel lifts/orthotics. Long-term prevention is achieved by continuation of the stretching program pre and particularly post golfing activity and the use of a semirigid neutral heel orthotic with consideration of a 4 mm medial heel skive and/or a 3 mm heel lift.

Plantar Fasciitis

Plantar fasciitis is an inflammation of the plantar fascial ligament which runs from the heel to the toes supporting the arch. This can be a common condition for golfers, especially for those who walk the course. Other risk factors include flatfeet or rigid cavus feet with improperly fitted golf shoes. Conservative treatment is successful in greater than 90% of the cases. Conservative treatment consists of stretching, icing, NSAIDS, decreased repetitive weightbearing activities, steroid injections, night splints, and biomechanical orthotic intervention. For golfers with flatfeet, one should fabricate a semi-rigid polypropylene orthotic with minimal arch fill and a medial heel skive. Additionally, if a forefoot valgus exists, a valgus extension will allow the first ray to plantarflex and reduce fascial tension. Depending on golf shoe choices, the orthotics may be able to be made wider and with a deep heel cup. Cavus feet require a more accommodative well-contoured insole with prominent arch support.

Neuroma

Golfers that suffer from a neuroma may have pain, numbness, tingling, and burning most often in the third interspace of the affected foot. Treatment involves wearing golf shoes wide in the forefoot to avoid compression to the nerve. Orthotics with a metatarsal pad can help decompress the interspace. Cortisone injections and NSAIDS are adjunctive therapies in relieving the condition.

Blisters

Blisters are commonly indicative of poorly fitting golf shoes or prominent pressure points of structural deformities of the foot. Treating the blister can be done by lancing the roof and decompressing the lesion but leaving the roof intact as a biological dressing. Antibiotic ointment and a bandage will allow for a decrease in pain, lessen the potential of infection, and return to sport. To prevent future blisters shoes must fit well, be waterproof, all prominent areas should be padded off, applying anti-chafing lubricants to the feet, and use socks made of synthetic materials that wick away moisture [28].

Summary

Golf shoes in the past had not been much more than a fashion accessory. Now with modern technology, golf shoes have evolved into a crucial game improvement tool. Golf shoes should now not only be comfortable but also offer stability to provide better balance, weight transfer, and power through impact. When determining what golf shoes to recommend, multiple variables need to be understood and taken into consideration. With so many varieties of golf shoes available in the marketplace, considering only foot type is now far too simplistic. Considerations such as level of play and swing type, cleat vs. cleatless, walk vs. ride, the need for orthotics, prior injuries, and even personal style need to be incorporated to maximize foot health, comfort, and performance.

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Tennis

21

Alex Kor

Tennis has changed substantially in the last 10–15 years. Tennis players are bigger, stronger, and more athletic [1]. They hit the ball faster, requiring quicker player responses. Racquet technology continues to improve. Wooden racquets are now collector's items and have been replaced by those made from a variety of other materials. Grass courts are slower, and hard courts are faster compared with courts of the past [2]. The strategy of the game has changed as well. There is less serve and volley play, and there are longer rallies involving more side-to-side movement of the players. Even the strokes have changed. Allan Grossman, DPM, United States Tennis Association Sports Science Committee, estimates that 70–80% of the baseline strokes are forehands and fewer than 30% are backhands (personal communication, June 2015). One might argue that the only part of the game that has yet to change substantially is the tennis shoe. Or has it?

As a former National Collegiate Athletic Association Division I tennis player at Butler University, who was nationally ranked #53 in my age group in 2014, I have experienced my own issues with tennis shoes (Fig. 21.1) and lower extremity pain. When I was taught the game in the 1970s, I used a wooden racket, was urged to perfect my backhand stroke, and hit white tennis balls. Tennis, like many sports of the day, did not offer athletes a wide array of footwear. Therefore, I provide my perspective as a podiatrist, and also as someone who has played tennis for more than 40 years.

The changes in the game of tennis influence what today's players require of their shoes. One of these changes is the technique of "sliding" on a tennis court, which seems to be second-nature for elite players from South America and Europe. Sliding allows players to recover quickly for an upcoming shot while maintaining foot position and momentum [3]. Sliding is rarely done on grass courts but is common on

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Fig. 21.1 Author's shoe showing wear of outsole

clay because of the softer surface. Players only began sliding on hard courts approximately 5–10 years ago (I have not yet mastered the technique). If you watch professional or college tennis played on a hard court, you will witness this technique countless times.

Sliding on a hard court (Fig. 21.2) developed as players adapted to the changing game of tennis. As a result of the faster speed of the game, taller height of the players [4], greater athleticism, and changes in string and racquet technology that allow for greater speed and spin on the ball, players have less time to prepare for the next shot. Instead of striking the ball in the conventional "hitting position" (Fig. 21.3), players now often use an "open stance" (Fig. 21.4). This change in technique saves the player time. Another modification is that players are now encouraged to hit fewer backhands (usually the weaker of the groundstrokes) and to hit more forehands. Thus, players "run around their backhand." This results in more lateral movement of the player on the backcourt and thus more sliding. Another change in the game that increases the reliance on sliding and more side-to-side backcourt play is the decreased emphasis on the net game. With less need to move forward to the net, players spend more time in the backcourt moving laterally.

Players face many considerations when choosing the appropriate tennis shoe. The optimal tread pattern on the sole differs according to the court surface. For clay courts, a tight tread pattern (e.g., herringbone) is best (Fig. 21.5) [5]. Grass courts typically require an outsole with dimpled tread or rubber studs to increase traction [6]. For hard courts, the most important factor is the durability of the rubber outsole.

A variety of rubber materials are now on the market. In 2014, Zhu [7] compared the non-slip performance of three sole materials: common rubber, abrasion resistance rubber, and adiWEAR composite (adidas AG, Herzogenaurach, Germany). Common rubber tested the worst, and abrasion resistance rubber tested the best. Conversely, in 2012, Clarke et al. [5] found that the type of rubber may not be as important as previously thought. That is, under different conditions (e.g., differences in court hardness, moisture, heat, humidity, size of clay particles) the same shoe may be better for providing grip one day and for sliding another day. They also suggested that the athletic ability of the player might play a role.

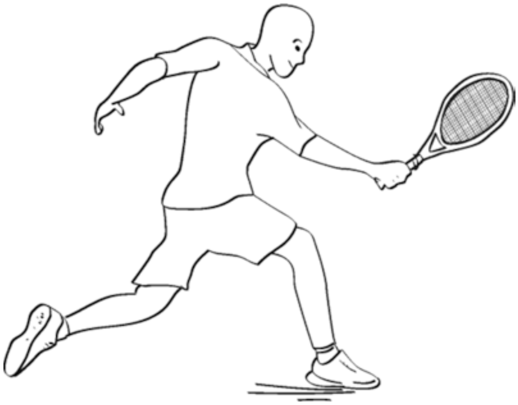

Fig. 21.2 Illustration of sliding on a hard court (© 2015 The Johns Hopkins University. Used with permission)

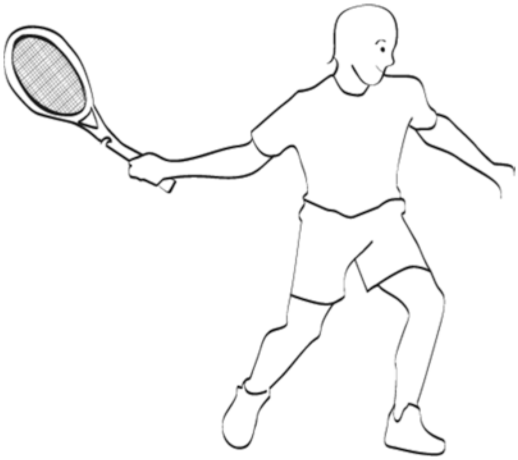

Fig. 21.3 Illustration of hitting position (© 2015 The Johns Hopkins University. Used with permission)

Fig. 21.4 Illustration of open stance (© 2015 The Johns Hopkins University. Used with permission)

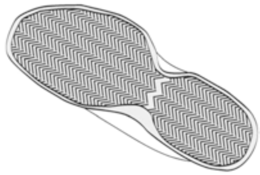

Fig. 21.5 Herringbone pattern of outsole on shoe used on clay courts (© 2015 The Johns Hopkins University. Used with permission)

Another important factor in shoe selection is the player's foot type and structure, which is commonly emphasized when purchasing a running shoe. Levy and Sharnoff make shoe recommendations by foot type in their annual review in Tennis magazine [8]. A supinated (or high-arched) foot (present in approximately 30% of tennis players [1]) is susceptible to lateral foot and ankle abnormality, as well as a lack of shock absorption. Thus, a player with a supinated foot needs a shoe with excellent cushion and a low or reduced-thickness midsole. Llana-Belloch et al. [9] reported that a shoe with a higher midsole can result in more lateral foot and ankle injury in a player with a supinated foot. Approximately 60% of all tennis players [1] have a pronated (or flat) foot. This foot type is predisposed to overuse conditions of the medial aspect of the foot and ankle. Therefore, preventing excessive pronation with motion control properties is the key to designing the best shoe for the athlete with this foot type.

Playing with little-to-no discomfort is critical to success in any sport. Reinschmidt and Nigg [10] and Bouche [11] suggested that the three most important factors for sport shoes are injury prevention, performance, and comfort. Knowing that cost also may play a role in shoe selection, I asked 25 of my fellow senior tennis players what factors motivate them to purchase a particular tennis shoe. All 25 responded to the multiple-choice question (four possible answers), citing comfort (88%), performance (64%), injury prevention (44%), and cost (44%). Obviously, these factors are interrelated. Playing tennis while in pain inhibits performance. If the shoe lacks sufficient comfort and support, then discomfort and injury rates will increase. In 2002, Llana et al. [12] surveyed 146 tennis players in Valencia, Spain, and analyzed their shoes for longitudinal and transverse flexibility. Of the participants, 67% reported that their shoes were extremely comfortable, very comfortable, or rather comfortable. Only 9.1% of respondents were uncomfortable in their tennis shoes. These data suggest that tennis players value comfort while playing tennis and are not (by and large) experiencing a lot of discomfort.

Other studies have found that there may be deficiencies in some tennis shoes. Huang [13] tested 15 male volunteers wearing two brand-named shoes (Adidas and Kappa [Torino, Italy]) in China. Using a plantar pressure distribution test system, he found no significant differences between the two shoe types but noted that the dampening aspect of the sub first metatarsal head and arch of the Kappa shoes should be improved. In a larger study, Sterzing et al. [14] surveyed 1524 tennis players from China, Germany, and the United States. All players were between the ages of 16 and 48 and had played tennis for at least 2 years. They reported various shoe-related problems, including forefoot outsole durability, foot sweating, blisters, pinched skin, and ankle twisting (Fig. 21.6). It is interesting to note that ankle sprains were less common in Germany (where there are more clay courts) and more

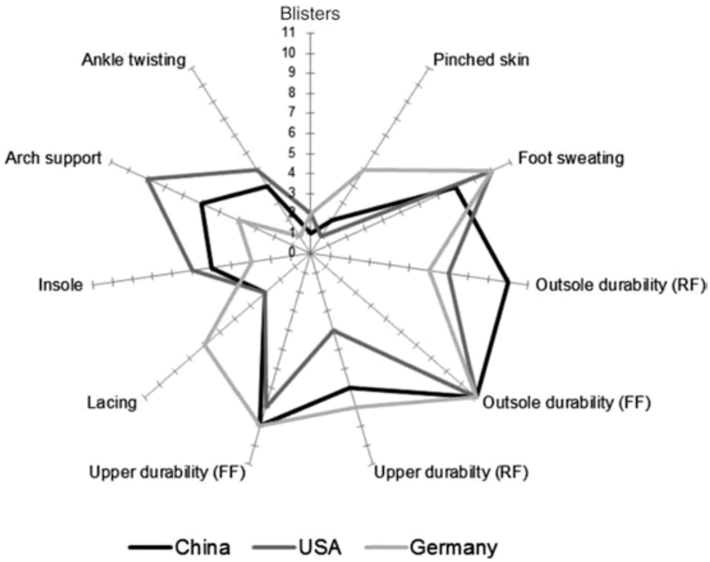

Fig. 21.6 Shoe problems for the total survey population. Likert scale mean ratings were converted into rankings with higher values indicating higher severity (reprinted with permission from Sterzing T, Barnes SA, Althoff KN, Determan L, Liu H, Cheung JTM (2014) Tennis shoe requirements in China, USA, and Germany. Footwear Science 6 3:165–176. Figure 6)

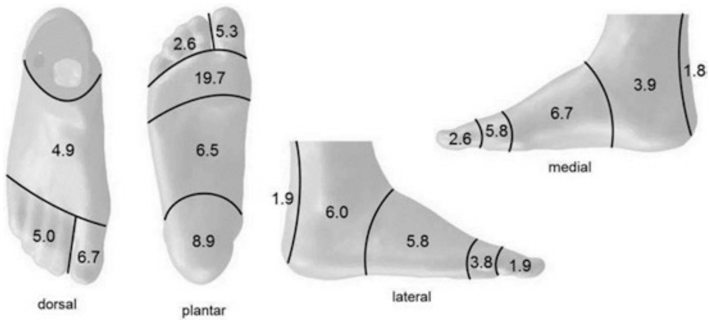

Fig. 21.7 Foot discomfort (pain) distribution (%) across foot locations for the total survey population (reprinted with permission from Sterzing T, Barnes SA, Althoff KN, Determan L, Liu H, Cheung JTM (2014) Tennis shoe requirements in China, USA, and Germany. Footwear Science 6 3:165–176. Figure 7)

common in China and the United States. Conversely, blisters and pinched skin were more prevalent in players from Germany who used clay courts. The plantar metatarsal head area (Fig. 21.7) was the primary site of pain reported by these players. The recommendation of Sterzing et al. is that "creation of innovative tennis footwear, providing increased forefoot shoe comfort marks a strong request of tennis players" [14] (p. 174). As a current tennis player, I agree with this request because I suffered

Fig. 21.8 Author's right foot showing torn capsule of second metatarsal phalangeal joint

Fig. 21.9 Radiograph of author's right foot showing lateral displacement of second toe

a torn capsule (Figs. 21.8 and 21.9) of my second metatarsophalangeal joint while playing a United States Tennis Association match in July of 2015.

Shoe companies seem to have decided that, like race cars, tennis shoes should be leaner and lower to the ground. As a tennis-playing podiatrist, I noticed this trend when many of my favorite mid-top tennis shoes were no longer on the market. As discussed with David Sharnoff, DPM (personal communication, June 2015), and Arthur Gudeon, DPM (personal communication, June 2015), the purpose of this shift in construction is to reduce the weight of the shoes without sacrificing durability and cushion. Some men's shoes now weigh less than 14 ounces (compared with 12.2–13.9 ounces in the past [8]). This is accomplished by using more mesh, breathable uppers, tennis-specific midsole material, and extra rubber in high-wear areas of the outsole. One wonders if shoe companies may be going too far in fashioning shoes like a Maserati.

In studying the cause of lower extremity tennis injuries, Nigg found that "in most cases, injuries to the lower extremity are surface related" [15] (p. 3). The author reviewed multiple studies that compared the rates of lower extremity injuries by court surface type. Injury rates were lowest on clay courts and second lowest on synthetic sand. Nigg concluded that the rate of injuries was four to eight times lower on clay courts than on other surfaces that did not allow for sliding. In addition, there is less muscle activation of the lower extremity on surfaces that enable sliding. Considering that sliding is now commonplace on hard courts at the elite level, one wonders whether lower extremity injuries on these courts will decline. To date, no definitive study exists.

Tennis is played worldwide by players of all ages and skill levels. Authors [11, 14] have noted that the direction of player movement and location of lower extremity injury consistently correlate with differences in player skill. Advanced players tend to rely on more side-to-side movement (and therefore, sliding), whereas novice players are more likely to move forward and backward. In addition, advanced players tend to spend most of their court time on the balls of their feet, whereas novice players spend more time flat-footed. The study comparing injury rates among tennis players in Germany, China, and the United States found that plantar foot discomfort was more prevalent under the metatarsal heads versus the heel area in players with greater skill level [14].

The use of orthotics in tennis shoes is not a new development. For the last 20 years, orthotic use by players of all levels has become common (in the 1990s, I was getting my orthotics from the same vendor as the legendary Pete Sampras). Some have argued that the use of over-the-counter and custom-made orthotics suggests that tennis shoes still lack important features [11]. I have found that the most practical reason for using orthotics is to improve a shoe that lacks a rigid shank. When those tennis players from Germany, China, and the United States were examined again, they found that the older American and German populations used the orthotics more than their Chinese counterparts [14]. In addition, they found that in the United States, the higher-skilled players relied more on these devices.

In summary, as a tennis-playing podiatrist, I have observed that as the game of tennis continues to change, the shoe industry is making every effort to keep up. David Sharnoff argues that the variety of tennis shoes on the market and the research and development of these shoes is on par with advances in footwear for other sports (D. Sharnoff, oral history, June 2015). Allan Grossman has data suggesting otherwise [16]. Using sensor technology embedded in tennis and running shoes, he wear-tested shoes worn by elite tennis players in 2011. Surprisingly, he found that running shoes tested better than tennis shoes in the same group of players. Grossman does not recommend playing tennis in running shoes, but he would like to see more running shoe technology used in tennis shoes. Perhaps shoe designers should try to mimic the "smart" tennis rackets that provide the player with stroke-by-stroke information. Can you envision the day that our tennis shoes will predict and manage our heel pain before it occurs? I can.

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Cycling

22

Paul R. Langer

Bicycling is a sport that is unique in that the human body functions as the engine of a machine. The energy to propel the machine forward is generated primarily by the lower extremity muscles and transferred to the bike's drive train through the pedals. Cycling as a sport as well as a mode of transportation has become increasingly specialized. Subcategories of bicycling sports include road biking, mountain biking, track racing, cyclo-cross (a combination of road and mountain biking), fitness (stationary, spin) cycling, and triathlon cycling. Each of the subcategories of cycling can employ different cycling positions and footwear/pedal systems. In addition to recreational cycling, the numbers of bicyclists who commute has been increasing. According to the US Census, the number of bike commuters increased by 9% between 1990 and 2000. The number of commuters will likely continue to increase due to increased funding of bicycle infrastructure.

Cycling Biomechanics and Considerations

Cycling Biomechanics

The lower extremity biomechanics of cycling is dominated by sagittal plane motion and has been referred to as a kinematically constrained task by some authors [1, 2] due to the restricted frontal and transverse plane motion. The lower extremity movement is primarily controlled by the predetermined circular path of the cycle pedal and crank arm [3]. Walking and cycling share some commonalities; both are bipedal locomotor tasks which alternate between flexion and extension with most power

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generated in extension [2]. Unlike weight-bearing sports where running impact and direction changes place strain on joints, cycling is a nonweight-bearing sport without impact forces or ballistic movements. However, in bicycling, the repetition of motion is much higher than any other sport. Highly trained and competitive cyclists often ride at cadences of 80–110 revolutions per minute which means that each lower limb is subjected to 4800–6600 revolutions per hour of riding.

There are a limited number of studies on the biomechanics of cycling and much of what has been published focuses more on pedaling efficiency and performance than on overuse injury mechanisms [4–6]. Just as with human gait, cycling biomechanics can be difficult to study due to high intersubject variability.

The Pedal Cycle

The pedal cycle consists of a power-generating phase which begins at 0° or "top dead center" (12:00 o'clock) and ends to just after 180° or "bottom dead center" (6:00 o'clock). The recovery phase then follows from bottom dead center back to top dead center. The power phase is marked by extension of the hip, knee, and ankle. Power is generated primarily by the gluteals, quadriceps, and gastro-soleus muscles. Gregor et al. found that the quadriceps and knee extensors were primary power sources in the first half of power-generating stroke while the hip extensors and ankle plantarflexors were primary in the second half [7]. During extension, the knee adducts and medially translates as the tibia internally rotates and the subtalar joint pronates [8]. Pedal reaction forces cause the midtarsal and subtalar joints to pronate and the medial column of the foot to invert and dorsiflex which in turn contributes to internal rotation of the leg [9]. Loads on the joints of the lower extremity are highest during the last 2/3 of the downward pedal stroke. Cyclists with clipless pedals (discussed in a following paragraph) can extend the power-generating phase by engaging the hamstrings to flex the knee and draw the pedal back as the foot passes through bottom dead center.

The recovery phase then follows the power phase. This phase is marked by flexion of the hip, knee, and ankle. With clipless pedals, the hip flexors, hamstrings, and tibialis anterior are active during this phase. Flexion of the hip and knee causes abduction and lateral translation of the knee as the pedal rises [9]. The ankle dorsiflexes and the subtalar joint re-supinates during the recovery phase.

Most competitive and serious recreational cyclists now use shoe/pedal systems that attach the rider's foot to the pedal through a cleat/binding interface. These systems are referred to as "clipless" pedals (Figs. 22.1 and 22.2). The advent of clipless pedals was initially heralded as an innovation that allowed the cyclist to generate power during the recovery portion of the pedal stroke but recent research has shown that at best even highly trained cyclists only partially unweight the pedal during recovery—they do not truly generate power [10, 11]. However, a mechanical advantage of unweighting the recovery phase leg may be that less force is required by the contralateral leg to "lift" the recovery leg. One study's conclusions suggest that the clipless pedals' greatest mechanical advantage may be not in allowing the cyclist to pull up during the last 180° of the pedal cycle but in pushing forward over top dead center and sweeping back at bottom dead center [12].

Fig. 22.1 Clipless pedal and cleat on outsole of shoe for road cycling

Fig. 22.2 Clipless pedal and cleat on outsole of shoe for mountain biking

Pedaling Technique

Competitive cyclists strive for an efficient circular pedal stroke that involves not just exerting a downward force during the first half of the stroke but also sweeping the foot backward at bottom dead center, pulling through the second half of the pedal stroke and then pushing the foot forward through the top dead center. This circular pedaling technique has long been presumed to be the most efficient; however there is not any scientific data that confirms this presumption. In fact, one group of researchers, after testing cyclists with four different pedaling techniques, found that cyclists were most metabolically efficient when pedaling in their preferred pattern [13].

Pedaling technique is almost as varied as running technique. Some cyclists may be "mashers" meaning that they ride in low gears at a low (40–60) rpm and exert force only during the downward portion of the pedal cycle. "Spinning," a technique using higher gears and higher rpms (80–100+), has been advocated as a more efficient pedaling technique but research does not confirm this. Some cyclists attempt "ankling," a technique where the ankle is plantarflexed during the power phase and dorsiflexed during the recovery phase. Just as runners and walkers self-select stride length and movement patterns to maximize metabolic economy and comfort [14], it has been suggested that cyclists will make technique, gearing, and cadence adjustments to alter pedal forces and maximize metabolic efficiency [15].

Pedaling Forces

Pedal forces acting on the foot are approximately half of bodyweight with seated pedaling and can approach up to three times bodyweight when standing, sprinting, or climbing [9]. Plantar pressures within the shoe are primarily localized to the forefoot and first ray while heel and arch plantar pressures remain low [16, 17]. Peak plantar pressure occurs between 90° and 110° of the pedal cycle [18–21]. Researchers have shown that stiffer cycling shoes increase peak plantar pressures when compared to less stiff shoes [17, 22]. Pedaling technique must be considered in injured cyclists as researchers have found that medial plantar loading increased with increased power output but decreased with higher rpm [16].

Much of what has been written on adjustments or modifications to address injuries or biomechanical faults has been described as trial-and-error processes. After selecting the proper frame size based on rider's height, parts of the bike can be adjusted to in accordance with a cyclist's body segment lengths. It is beyond the scope of this chapter to discuss the theory and practical applications of fitting the rider to the bicycle; however those who regularly treat cyclists and triathletes should become familiar with bike fit.

Cycling Injuries and Risk Factors

Risk factors for overuse cycling injuries include training errors, poor pedaling technique, improper bike fit, anatomical malalignment, biomechanical faults, muscle imbalances, and inadequate cycling equipment. For all injured cyclists it is important to evaluate training distance and intensity, other athletic activities (many cyclists cross train and/or weight train), bike fit, anatomic factors such as muscle imbalances, lower extremity biomechanics, flexibility/ROM, limb length asymmetry, and previous injury history. As with any athlete, activity modification and symptomatic treatment are important in addressing the injured cyclist.

There is a lack of evidence-based biomechanical treatment of cycling injuries. Many experienced cycling sports medicine specialists describe anecdotal and trial-and-error treatment methods. Most authors agree that addressing faulty biomechanics is important to prevent recurrence of injury in many cyclists. Excessive subtalar joint pronation has been linked to patellofemoral pain, iliotibial band syndrome, Achilles tendonitis, plantar fasciitis, metatarsalgia, and forefoot neuritis. Limited subtalar joint pronation and cavus foot type have been linked to sesamoiditis, Achilles tendonitis, extensor tendonitis, metatarsalgia, and forefoot neuritis as well [23].

Most research on bicycling injuries is focused on the area of traumatic injuries [24, 25]. Overuse cycling injuries are just starting to receive more attention from researchers. In a survey of 473 recreational cyclists researchers found that 85% had experienced an overuse injury [26]. The knee was the most commonly injured lower extremity site ranging from 35 to 65% or riders and females reported higher incidence of knee pain than males [26–28]. Foot injuries were reported in 15.6% and ankle/Achilles injuries in 7.3% of cyclists [26]. Many cyclists report chronic discomfort especially to the neck, butt, hands, and feet related to riding which they may not classify as an injury but more as a nuisance or discomfort.

Cycling Footwear

Cycling shoes, like other types of footwear, have become increasingly specialized. Since the shoe is only a part of the foot/shoe/pedal interface, this section also discusses cleats and pedal systems.

The perfect cycling shoe transmits energy efficiently to the pedal yet distributes forces evenly, dampens vibration, does not bind the foot, and allows heat/moisture dissipation while offering resistance to weather conditions. Sport-specific cycling shoes combined with a cleat and pedal system have been shown to increase pedaling efficiency [18]. Unlike many other sports where shoes are selected for fit, comfort, and biomechanical considerations, cyclists must select their footwear based on the type of cycling they participate in (road, touring, mountain), and type and brand of pedal system they will use, and then select the shoe with appropriate fit and comfort for their foot. For cyclists who choose to use a clipless pedal system, once they have purchased shoes they must then purchase cleats and attach the cleats to the shoe's outsole with bolts.

The unique structural features of cycling shoes are the stiff midsole/outsole and the cleat holes. Efficient energy transfer from the foot to the pedal is optimized with stiff materials [3]. Manufacturers of cycling footwear use rigid materials in the midsole/outsole for its ability to resist longitudinal as well as torsional bending. Less expensive and recreational cycling shoes are often made with plastics. More expensive and racing-oriented cycling shoes are made with carbon fiber composites which are lighter and more rigid. The more rigid materials have also been shown to increase peak plantar pressures in cyclists which have implications for those who experience foot pain [22].

The conflict that some cyclists encounter with cycling footwear is that structural features designed to enhance performance such as snug fit and stiff outsoles have also been linked to decreased comfort and foot pain. Some cyclists who experience significant foot pain or discomfort may benefit from less performance-oriented but more comfortable footwear. Some researchers have found that a lack of comfort negatively affects performance and increases the risk of injury [29, 30].

Cycling Shoe Fit

Much like skiers and skaters, competitive cyclists will fit their shoes to be snug so that there is minimal motion of the foot inside the shoe and maximal energy transfer to the shoe interface. Recreational cyclists are more willing to make performance allowances in favor of comfort and walkability. Ideally, the cycling shoe is snug in the heel and midfoot to minimize wasted motion and provides adequate forefoot length and width to minimize discomfort. Allowances in toe room are common to accommodate foot edema experienced in weight-bearing endurance sports like running but research has shown that cyclists do not increase foot volume due to edema at shorter intervals of cycling activity [31]. As with any footwear there should be minimal side-to-side pressure at the widest part of the foot which usually corresponds to the first metatarsal phalangeal joint and fifth metatarsal phalangeal joints of the foot. The midfoot fit should be snug without creating pressure. Cycling shoes that are too loose in the midfoot will cause the cyclist to compensate by overtightening the closure system which may result in discomfort or dorsal foot injury. Heel fit of cycling shoes should not allow pistoning of the heel inside the shoe.

Some brands of cycling footwear are available in wide sizes and recently custom cycling shoes have become easier to find. Manufacturers are starting to introduce off-the-shelf shoes that can be heated and molded to the heel and arch. In addition, some manufacturers have started to offer shoes made on women-specific lasts.

Cycling Shoe Construction

Cycling shoe construction is discussed below. Three general categories of cycling shoes will be described: road, sport, and mountain biking shoes (Fig. 22.3).

Road Cycling Shoe Construction

Like ski boots, road cycling shoes are not made for walking. The rigid sole and external cleat allow for only minimal walking. They are designed to be light, stiff, snug structures that allow the nonweight-bearing foot to transfer force efficiently to the pedal while minimizing wasted motion of the foot within the shoe.

Fig. 22.3 Sport shoe, mountain bike shoe, road shoe

Last

Road cycling shoes are lasted much like track spikes, on a curved "performance" last with a board-lasted footbed. Performance lasts provide a low-volume, snug fitting upper and are narrower than conventional lasts. The board last combined with the stiff midsole/outsole provides rigidity for maximal energy transfer.

Upper

The road shoe upper is typically made of a fabric mesh, leather, and/or synthetic materials that allow for maximal ventilation. A rigid heel counter is incorporated to minimize rearfoot motion. The shoe's upper is secured to the foot with laces, ratchet-style buckles, Velcro straps, cable and rotary dials, or a combination thereof. The tongue is padded to distribute pressure of the closure system on the dorsal foot. High-performance racing shoe models will have a shroud or low-profile closure system to minimize wind resistance. Triathlon cycling shoes are road cycling shoes with simpler closure systems (such as a single Velcro strap) to allow for quick entry/exit. They usually have a seamless or fabric liner since some triathletes prefer to cycle without socks.

Footbed/Insole

Most cycling shoes are now made with removable insoles which can vary in quality and features. Many resemble the footbeds found in running shoes and may be made from closed cell foams or ethyl vinyl acetate and have a wicking fabric top cover. More expensive models may incorporate arch support, metatarsal support, or plastic shells.

Midsole/Outsole

In order to minimize weight and maximize stiffness, the midsole also serves as the outsole in road shoes. High-performance road shoes are made with the lightest, stiffest materials such as carbon fiber composites. Recreational road shoes use nylon which is still relatively stiff but heavier and less expensive than carbon fiber. Some cycling shoes incorporate the heel counter into a one-piece midsole construction. This helps lend significant stiffness to the shoe while minimizing weight. One manufacturer has introduced shoes that incorporate a forefoot varus wedge of 1.5° into the outsole [32]. The performance road cycling shoe outsole typically curves in the sagittal plane. This outsole shape slightly dorsiflexes the digits and, when the cleat is engaged with the pedal, facilitates plantar flexion of the ankle (Fig. 22.4). Most road cycling shoes are compatible with external cleats that attach the shoe to a pedal much like a binding attaches a boot to a ski. Road cycling shoes come with predrilled holes in the forefoot for placement of the external cleats. This exposed cleat design raises the foot off of the pedal and makes walking in road shoes difficult (Fig. 22.5).

Outsole

Some road shoes may have small rubber bumpers on the toe and heel for walking traction. In an effort to remove every last gram of unnecessary weight, racers often remove the bumpers.

Fig. 22.4 Road cycling shoe engaged with pedal

Fig. 22.5 Road shoe with external cleat

Sport Cycling Shoe Construction

"Sport," "trail," "fitness," "touring," and "recreational" are all terms used for cycling shoes that tend to be more comfortable than road shoes yet also allow attachment of recessed cleats. They are designed with less emphasis on performance and more emphasis on comfort and walkability. Unlike road cycling shoes which are too rigid and have an external cleat which makes it almost impossible to walk, this category of cycling shoe is easier to walk in. Sport cycling shoes are usually heavier, less aerodynamic, and more flexible and may have little to no sagittal plane curve when compared to road shoes. This category of cycling shoe is popular with commuters, casual riders, cycle tourists, stationary fitness class participants, and those who simply cannot comfortably wear road shoes. Sport cycling shoes also may accommodate certain types of custom orthoses better than road shoes.

Last

Sport cycling shoes are lasted on semi-curved or semi-straight lasts much like walking and hiking shoes. The conventional last provides more width and volume than that found in road shoes. Most have a board last to provide some stiffness and torsional resistance.

Upper

Uppers are constructed of mesh fabrics, and leather or synthetic materials. Most sport cycling shoes use laces but some have Velcro straps, buckles, or a combination of closure systems. Plastic heel counters are incorporated into the upper along with a padded collar and tongue. The uppers often resemble hiking or walking shoes and in fact are often indistinguishable. The larger volume upper of recreational cycling shoes makes them a better choice for those with exceptionally wide feet, or those who are uncomfortable in the stiff, snug road shoes.

Footbed/Insole

Like road shoes, most sport shoes now come with a removable insole that may incorporate padding, metatarsal, and arch support. Some footbeds offer minimal protection from the cleat bolts in the forefoot.

Midsole

Some sport shoes incorporate a polyurethane midsole to provide additional cushioning and walking comfort and may have a dual-density midsole as well. Some sport shoes will reinforce the midsole with fiberglass to lend more rigidity.

Outsole

Sport cycling shoes are constructed with carbon rubber outsoles and can be used with or without a recessed cleat (Fig. 22.6). The outsole is stiffer than a conventional hiking/walking shoe yet still provides traction and versatility when off the bike and is significantly less stiff than a road cycling shoe. Outsoles may come with predrilled bolt holes for cleats or may have a section under the forefoot that can be removed for placement of recessed cleats. The recessed cleat design protects the cleat from debris and makes walking much easier than road shoes.

Mountain Biking Shoe Construction

Mountain biking (MTB) shoes are also popular for their comfort but have other unique features since mountain biking often requires cyclists to dismount their bikes to navigate obstacles such as logs, rocks, or streams. For this reason, MTB shoes have a more aggressive outsole traction design, a recessed cleat, and a rubberized sole for traction during walking. Some MTB shoes may be considered a hybrid of road and sport shoes—combining the performance features of the road shoes and for some the comfort features of the sport shoes. Within the category of MTB shoes there are shoes geared more for racing and competitive riders and those for more recreational MTB riders. Racing MTB shoes often resemble road shoes with recessed cleats and rubber outsoles while the recreational MTB shoes are

Fig. 22.6 Outsole of sport shoe without cleat

more similar to the sport cycling shoes. The recessed cleat is protected from weight bearing and is less vulnerable to damage or to picking up debris such as mud like the external road cycling cleat would.

Last

Competition MTB shoes are lasted on a performance board last like road shoes but recreational MTB shoes will offer a standard curved or semicurved board last.

Insole/Footbed

Like road and sport shoes, most MTB shoes now come with a removable insole that may incorporate padding, metatarsal, and arch support. Some footbeds offer minimal protection from the cleat bolts.

Midsole

The midsole of an MTB shoe may be made with stiff nylon, fiberglass, or carbon graphite. Some shoes will use a polyurethane midsole reinforced with a plastic or fiberglass plate for stiffness.

Outsole

Rubber sheet or studs: MTB shoes have threaded bolt holes drilled through the outsole for placement of a recessed external cleat (Fig. 22.7). Most MTB shoes have a rubber outsole with a rectangular rubber window that can be removed so

Fig. 22.7 MTB outsole with recessed cleat

Fig. 22.8 Cleats attached to shoes outsole, left two shoes are external, right shoe is recessed

that a cleat can be added to the shoe if the cyclist chooses. Toe-and-heel spikes may be found on the outsole of racing MTB shoes. The spikes resemble those found on soccer or football spikes and provide traction in mud. Some models have removable spikes.

Selecting the appropriate type and model of shoes is only a part of the decision making process for many cyclists. Many will then purchase a cleat and pedal system as well. The interface of the shoe with the bike is via the cleat and pedal system and we would be remiss in a chapter on cycling footwear to ignore this important component of cycling. In many ways, cleats and pedals have become more technically sophisticated than the footwear.

Cycling Cleats

Cleats attach the shoe to the bike through an engineered pedal system (Fig. 22.8). The cleat/pedal interface is a single point of attachment at the ball of the foot. The cleat is attached to the sole of the shoe with bolts. The pedal is engaged by placing the cleat over the pedal and exerting a downward force until the spring-loaded pedal accepts the cleat. (One popular pedal/cleat system manufactured by Speedplay® places the spring in the cleat instead of the pedal.) Most cleats are released from the pedal by externally rotating the heel. Some cleats can be released in multiple directions. Many pedals have adjustable tension so that the force required to release the shoe can be altered as needed. For example, newer cyclists may prefer a lower tension setting for ease of exit from the pedal while experienced cyclists, like aggressive mountain bikers, may set the tension higher to minimize the risk of early release from the pedal.

Road cycling cleats are usually made from lightweight plastics or metals while most MTB cleats are made from stainless steel. The plastic, externally mounted road cleats are more prone to wear than the recessed metal MTB cleats but both must be replaced regularly. Look (Salt Lake City, UT) introduced their cleat/pedal system in the mid-1980s that remains the most commonly used road cycling pedal system. Speedplay pedals (San Diego, CA) introduced pedals with the highest degree of rotational freedom; Shimano (Irvine, CA), the maker of the recessed SPD (Shimano Pedaling Dynamics) pedal system, is the most common MTB and commuter cyclist pedal system.

The first clipless cleat/pedal systems locked the foot in and allowed only sagittal plane motion about the pedal spindle, allowing zero degrees of internal or external rotation of the foot during the pedal cycle. But an innovation that has had implications on cycling injuries is the cleat/pedal system that allows internal/external rotation of the foot about the pedal's transverse axis. This rotation is referred to as "float" in cycling jargon and allows the cyclist varying degrees of freedom during the pedal cycle. Some performance pedals can be adjusted for the desired amount of float. For some pedal systems cleats are color coded to indicate how many degrees of float they allow. Pedals may allow up to 15° of float.

The location and alignment of the cleat on the shoe can be adjusted to address lower limb alignment or injuries. This is discussed in more detail in the sections on pedals and foot position.

Pedals

Pedals vary in shape and performance features. Bicycling pedals have evolved from a relatively large platform for conventional shoes to today's engineered pedal systems that attach a special cycling shoe to the pedal via a binding system. "Toe clips" were the first pedaling innovation which used a strap and cage over the forefoot to secure the foot to pedal, increasing pedaling efficiency and minimizing the risk of the foot slipping off the pedal. While the strap secured the shoe to the pedal it still allowed some freedom in foot position. Disadvantages of toe clips include forefoot discomfort due to the tight strap and manually having to loosen the strap to enter/exit the clips. Some recreational cyclists prefer toe clips to standard pedals and to the newer "clipless" pedal designs.

In the 1980s "clipless" pedal systems were developed which used an external cleat on the shoe's forefoot that attached to a spring-loaded pedal much like ski bindings attach a boot to a ski. The pedals are engaged by placing the cleat over the pedal and exerting a downward force. They are released by externally rotating the heel. The spring tension of the pedal can be adjusted to make release easier or harder depending on the demands of the cyclist. Much like skiers and ski bindings, competitive cyclists will set the spring tension higher to minimize the risk of early release from the pedal. Recreational cyclists prefer an easier release and lower spring tension. In some pedal systems the spring tension can affect the rotational ability of the pedal. Clipless pedals allow the rider to increase pedaling efficiency by minimizing some of the "dead spots" in the pedaling cycle, allowing the rider to recruit more muscle groups and to unweight the leg on the upstroke [33]. Clipless pedals also allow greater ankle plantarflexion and shear loads on the downstroke which helps to extend the power-generating portion of the pedal cycle past bottom dead center [18]. One study found that clipless pedal systems were preferred by 57.1% of cyclists who had participated in an organized bike ride [26].

Multiple pedal/cleat systems are available today each with its own performance features. Injured cyclists or cyclists who are vulnerable to foot pain may have to consider whether a different pedal system may have features that are more appropriate for their needs. For example, some pedal systems have more rotational freedom which may be significant for those with knee injuries. Those with chronic forefoot pain may benefit from a pedal with a larger surface area to better distribute pressure.

An important cleat/pedal feature allows transverse plane foot rotation. Since cyclists exhibit varying amounts of in-toeing/out-toeing during different points of the pedal cycle it became necessary to allow some degree of adjustability and freedom in the transverse plane. More rigid cycling shoes and the fixed position of the cleat/pedal interface likely place undue stress on the knee [34]. Conversely some authors have implicated excessive rotational freedom as facilitating faulty knee and foot mechanics [35, 36]. Pedal/cleat systems that allow some freedom in the transverse plane are widely available.

Road cycling pedals are engineered to be lightweight and low profile. They are manufactured from plastic, aluminum, metal alloys, or titanium. More expensive pedals offer adjustable spring tension and adjustable degrees of float and are made from exotic metals such as titanium. The weight savings has obvious energy-saving benefits. The low pedal profile makes the pedal more aerodynamic as well as allows more ground clearance in high-speed turns. The small surface area of some pedals concentrates the local plantar foot pressures. Some road pedals are double sided allowing articulation with the cleat regardless of which side of the pedal is facing up.

MTB pedals are engineered to resist mud and debris yet allow easy exit/entry. Most MTB pedals are double sided meaning that they have cleat receptacles on both sides of the pedal making it easier to clip in even if the pedal has rotated. Some MTB pedals combine the conventional pedal platform with the binding system. This makes the pedal easier to use for casual rides in conventional shoes as well. Most commuters prefer MTB shoe/cleat/pedal systems because of their versatility.

Foot Position on the Pedal

The cleat can be moved proximal/distal, and medial/lateral, or rotated in the transverse plane.

Most authors recommend placing cyclists in neutral lower extremity position to minimize risk of injury [37]. But there is no agreement on how to determine transverse plane neutral foot cycling position. One method of determining optimal transverse plane position of the foot on the pedal uses a device called a rotational adjustment device (or RAD) (FitKit Systems, Billings MT) and is placed on the pedal while the cyclist pedals on a stationary wind trainer. Some retail cycling shops or bike fit technicians use the RAD system when fitting bikes. Multiple authors advocate the benefits of this fit system [9, 38, 39]. Some pedal systems allow greater degrees of rotational freedom about the forefoot which makes for a larger margin for error or even obviates the need for setting the cleat in a neutral position.

Additionally, shims and wedges can be placed between the cleat and sole to address limb length inequality or forefoot varus/valgus as well as knee varus/valgus [35].

Cycling Insoles

Recognizing the benefits of comfortable footbeds, many cycling shoe manufacturers are now making their shoes with higher quality, removable insoles. The insoles often incorporate some medial longitudinal arch support and/or some transverse metatarsal arch support. The benefit of the removable insoles is twofold in that the insoles can be modified with additional arch support or metatarsal pads or replaced with custom orthotics to improve foot function.

Replacement insoles are also now more widely available. Some insole manufacturers are making an insole that is compatible with the lower volume last of the road cycling shoe and is often very similar to a replacement ice skate insole. Since touring and MTB shoes are lasted much like conventional athletic shoes, most prefabricated insoles will fit well. Some cycling shoe manufacturers are producing replacement insoles that are sold with forefoot varus/valgus wedges and/or arch support devices that may be added or removed to address forefoot misalignment and arch height [40]. A recent study on such an insole with forefoot varus wedges showed no significant changes in cycling kinematics between conditions utilizing 1.5, 3.0, and 4.5 mm varus wedges under the forefoot [41]. Another study showed that a commercially available contoured insole significantly increased plantar surface contact area through the medial and lateral midfoot [42]. The altered plantar surface contact can be important to cyclists who have issues either with comfort and/or foot pain.

Cycling Orthoses

Custom foot orthoses have been used in cycling to correct biomechanical faults, reduce pedal/in shoe pressure, and balance limb length inequalities (Fig. 22.9). However, there is little research into the efficacy of orthotic management of cycling biomechanics and injuries. For weight-bearing activities custom orthoses have been shown to decrease peak plantar pressures and reduced foot pain [43, 44]. Additionally, custom foot orthoses have been shown to alter subtalar joint pronation, decrease internal tibial rotation, and decrease knee loads [45–47].

Fig. 22.9 Cycling orthosis with intrinsic rearfoot post on rigid shell, reverse Morton's extension, metatarsal pad, and full-length top cover

The snug fit and stiff soles of road cycling shoes and nonweight-bearing nature of the sport make intrinsic rearfoot posts and rigid shell materials the best choice [9, 48]. There are limitations to the amount of extrinsic modifications which can be made to the orthosis due to the snug fit and narrow last of most road cycling shoes. Touring and MTB shoes can often accommodate extrinsic rearfoot and forefoot posts and bulkier shell materials. Because the forefoot is the site of articulation with the pedal most orthoses and insole interventions are focused on this area. In addition, supporting the medial longitudinal arch and/or limiting subtalar joint pronation can improve foot mechanics, distribute plantar pressures, and increase comfort.

Anderson and Sockler tested cycling subjects' oxygen consumption in three different shoe/orthoses states and found that, while not statistically significant, there was a trend toward increased cycling efficiency with use of orthoses as workloads approached maximal loads [12].

Socks

Cycling socks are made from synthetic fabrics that wick moisture. Lightweight socks are used in warm weather and thicker socks are used in cooler weather. Some triathletes choose not to wear socks for cycling and many of the triathlon-specific cycling shoes are made with a flat-seamed fabric liner. In cold or inclement weather many cyclists wear a waterproof or insulated booty over their cycling shoes.

Footwear Recommendations and Modifications for Prevention and Treatment of Injury

Cycling shoes are selected based on type of cycling, pedal type, and fit. Unlike running shoes, there is not a significant variability in terms of lasts. Since sport and some MTB cycling shoes tend to have larger volume uppers, a more flexible outsole, and straighter lasts than road cycling shoes, they offer some versatility for treating cyclists with chronic foot pain/injuries or difficult-to-fit feet. Many of the most common shoe/cleat/pedal modifications used by cyclists and bike fitters have been handed down from the trial-and-error treatment methods used in competitive cycling for decades.

Knee Pain

Causes of knee pain include training errors such as pushing high gears or excessive hill training, bike fit issues such as improper saddle position or improper shoe/cleat position, and anatomical factors such as limb length inequality, overpronation, genu varum/valgum, ligamentous laxity, high Q angle, and muscle imbalances among other causes [8, 23, 39, 49–51]. Common diagnoses of patellofemoral pain may be chondromalacia, patellar tendinosis, prepatellar bursitis, plica syndrome, and patellar subluxation. Other causes of knee pain include pes anserine bursitis and iliotibial band syndrome.

Faulty mechanics at the foot/shoe/pedal interface has been linked to each of these conditions by multiple authors. One group of researchers found that improper cleat alignment was the most common problem in those with patellofemoral pain [49]. Others found that both axial and varus/valgus knee moments were significantly reduced with pedals that allowed freedom in the transverse plane [52]. In addition seat position that is too high, too low, or too far forward has been linked to excessive patellofemoral loading by causing excessive knee flexion at the top of the pedal stroke [50]. Excessively long crank arms have also been implicated in increased forces acting on the patellofemoral joint [8].

The high pedal forces generated during the power phase of cycling have been implicated in increased subtalar joint pronation and chondromalacia [51].

Since excessive loads on the knee occur during the power-generating stroke in cycling, optimizing alignment and minimizing torsional forces have often been the focus of biomechanical treatment. Foot/shoe pedal alignment and seat position changes may reduce knee strains. Spring tension of the pedal release mechanism can affect the rotational abilities of the pedal and must be considered in cyclists with knee pain. Much attention has been directed at controlling torsional forces on the knee by controlling subtalar joint pronation with medial longitudinal arch support and forefoot varus wedging.

Custom foot orthoses can be used to correct functional foot disorders that may be contributing to knee pain. Correction of frontal plane deformities with appropriate forefoot and rearfoot posting has been used as an efficacious therapy for treatment of patellofemoral pain [53].

Using video analysis, Francis described decreased knee valgus in cyclists after introducing an orthosis [54]. Ruby and Hull, using a modified pedal that allowed eversion/inversion, were able to decrease varus and valgus knee moments [55] which suggests that forefoot posting of the shoe/foot/pedal interface such as with orthoses would have similar effect.

Iliotibial Band Syndrome

Inflammation of the iliotibial band (ITB) is commonly caused by anatomic abnormalities or poor bike fit which may contribute to friction of the ITB over the lateral femoral condyle during flexion and extension of the knee. Improper cleat alignment, limb length inequalities, excessive pronation, poor bike fit, and varus knee alignment are common contributing factors [8, 39, 49]. Shoe/pedal adjustments include using shims or spacers between under the cleat to balance limb length and/or orthoses to control hyperpronation. Cleats may need to be placed with more external rotation or a cleat/pedal system with more rotational freedom may benefit some cyclists.

Limb Length Inequality

For injuries that may be attributable to limb length inequalities, such as patellofemoral pain, hip/low back complaints, Achilles tendonitis, or iliotibial band syndrome, two methods of adjustment have been described. As is generally accepted anecdotally for weight-bearing activities, correcting approximately half of the suspected limb length is often a good starting point. Limb length can be compensated for by setting the saddle height to the longer limb and then adding a shim between the cleat and sole of the shoe on the short limb. An additional technique, for smaller limb length discrepancies advocated by Andy Pruitt, the former chief medical officer of US Cycling, involves shifting the cleat 1–2 mm distal on the short limb for measured limb length differences of less than 6 mm [56].

Achilles Tendon and Posterior Heel Pain

Rearfoot pain may be caused by Achilles tendonitis, retrocalcaneal bursitis, Achilles enthesopathy, and retrocalcaneal exostosis (Haglund's bumps). The heel cup and collar of the cycling shoe must be evaluated for proper fit. Seat height must be assessed for possible contribution to excessive dorsiflexion of ankle at top dead center of pedal cycle [39]. Appropriate shoe modifications include offloading pressure with adhesive felt padding to the inside of the heel counter, addition of a heel lift, addition of rubber heel cup, or permanent structural modification of the heel counter or upper by a skilled shoe repair shop. Insole modifications and orthoses that address biomechanical factors such as overpronation and/or equinus may be of benefit as well.

Plantar Fasciitis

While plantar fasciitis does not appear to be as common in cyclists as it is in weight-bearing sports, it is possible to address the symptoms in the cycling shoe. Low seat height can be a contributing factor [57]. Rubber or silicone heel cups may be added to shoes. In addition, the insoles can be modified with the addition of adhesive felt padding to support the medial longitudinal arch. Full-length orthoses may be used to address any contributing biomechanical factors.

Forefoot Pain and Injuries

Foot injuries were reported twice as often as ankle and Achilles injuries in one study of recreational cyclists [26]. Because of the concentrated pedal reaction forces at the foot/shoe/pedal interface, cyclists are much more likely to suffer forefoot pain than midfoot or rearfoot pain. The small surface area of the pedal, stiff soled shoes, and plantar pressure generated by the pedal stroke can all combine to stress the soft tissue and osseous structures of the forefoot more than the rearfoot.

Ischemia has been proposed as an injury mechanism due to the constant pedal reaction force against the plantar forefoot [17]—cyclists often refer to this pain as "hot foot." Tight shoes, stiff soles, toe straps, high gear–low-cadence pedaling technique, improper cleat position, and small pedal surface area have also been suggested as common causes of forefoot pain in cyclists [23]. In addition to ischemic paresthesias, forefoot pain may be caused by; metatarsalgia, sesamoiditis, capsulitis, and Morton's neuroma.

Cleat position is important in addressing forefoot pain. Most riders will have their shoes positioned so that the cleat is directly under the metatarsal heads. This location has been suggested as the optimal location for energy transmission but it can cause pain in some riders. Most cleats can be moved anterior and posterior as well as medial and lateral. A more proximal placement of the cleat has been suggested as a means of relieving many pressure-induced types of forefoot pain [36, 56].

Researchers have found that as power output increases pressure shifts to the medial forefoot. One study found that medial plantar loading increased with higher power outputs and decreased with increased cadence. This decrease was most pronounced under the first met head and toes and less under the fifth met head, midfoot, and heel [58].

Insole modifications for forefoot pain include forefoot cushioning, addition of metatarsal pads, aperture pads, use of forefoot extensions such as varus/valgus wedges, and addition of medial longitudinal arch support. The shoe's footbed should be evaluated for protruding cleat bolts or manufacturing defects as well. As mentioned previously, many cycling shoes now are made with removable insoles which allow for modification or replacement. Metatarsal pads have been shown to decrease plantar forefoot pressures but their effectiveness is dependent on location and size [59, 60]. Metatarsal pads can be effective in relieving pain due to Morton's neuroma, pressure-induced ischemia, metatarsal capsulitis, sesamoiditis, or metatarsalgia. Additional cushioning can be added to the forefoot with replacement insoles.

Orthoses for forefoot pain should use a rigid shell material, intrinsic rearfoot, and full-length cushioned top cover [9]. Because of the high forefoot forces cycling orthoses should include metatarsal support in addition to control of biomechanical factors such as hyperpronation [8]. Metatarsal pads, extrinsic forefoot posting to sulcus, aperture pads, or Morton's extension/reverse Morton's extensions can be incorporated as needed. Road shoes will require a narrow shell to fit inside the performance-lasted upper; sport and MTB shoes may accommodate a standard shell shape.

The Future of Cycling Footwear

Footwear manufacturers are increasingly moving toward the mass customization. The manufacturing infrastructure is slowly being adapted so that custom footwear can be measured, fit, ordered, and produced more economically and more quickly than ever imagined before. Custom-made cycling shoes and insoles will likely become more widely available and more affordable in the coming years. Performance-enhancing and comfort-enhancing features will likely continue to evolve.

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23 Court Shoes and Orthoses for Racquet Sports: Tennis, Pickleball, Badminton, Squash, Racquetball, and American Handball

Richard T. Bouché

Introduction

Racquet sports make up an eclectic group of court activities that can be quite diverse. In this chapter we will focus on the following racquet sports: tennis, pickleball, badminton, squash, racquetball, and American handball[1]. Though it is beyond the scope of this chapter, it is paramount that readers become acquainted with specific background information on each of these individual sports including developmental history, rules and strategies, and necessary equipment. This information gives the reader "credibility" in dealing with racquet sport athletes and also provides a solid foundation for further study.

Court Design and Surfaces

Being familiar with court design and the various surfaces these sports are played on is paramount as this information will dictate type and features of shoes that are recommended for each racquet sport [1–3]. This knowledge base will also have a profound effect on sport performance, comfort, etiology, treatment, and prevention of injuries.

Concerning court design, tennis, pickleball, and badminton are played on "open" courts (no walls). American handball, squash, and racquetball are played on "closed"

[1] American handball does not require use of a racquet but does mandate use of a glove on each hand. It was included in this chapter because of its close similarities to racquetball from which it was derived. American handball needs to be differentiated from European handball (also called team handball) which is a team sport played on an open court.

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courts with four walls, and in the case of racquetball and handball, a ceiling as well. Each of these courts has standardized dimensions.

Tennis is a sport that is played both indoors and outdoors on a large number of varied surfaces. There can be much confusion on terminology used to categorize tennis court surfaces with terms such as hard, soft, cushioned, fast, and slow, which are commonly used though poorly defined. For sake of simplicity and this discussion, tennis surfaces will be divided into four general categories: carpet, grass, clay, and hard court [4].

Carpet surfaces are typically used for multiple sport use and are the least common surface used in tennis. This surface can be made out of various synthetic materials (rubber, vinyl, or nylon) with multiple proprietary products being available. Rubber and vinyl surfaces are generally slow to medium and nylon is fast.

Tennis was originally known as "lawn tennis" as grass was the traditional surface to play on. Today grass is uncommonly used in the Unites States due to meticulous maintenance demands at high costs. Grass is still common in Britain and Northeastern US. Grass courts offer the fastest surface today and is the court surface used at Wimbledon favoring players who prefer serve-and-volley and net play. Backspin is particularly effective on grass.

Clay courts are basically crushed shale, stone, or brick and are colored either green (popular in eastern USA) or red (popular in Europe). This surface is the slowest tennis court surface with characteristic high-bouncing balls. Due to the low friction coefficient, players commonly slide much during play. Skidding of the ball is common as it contacts the 2″ white line markings. This court surface favors the baseline player and is temperature dependent which can affect ball trajectory after it strikes the court. Backspin is also effective on clay courts. The French Open is played on red clay.

Hard courts are the dominant surface in the United States though there is great variability in court surfaces due to various proprietary formulas used for installation. Typically, hard courts can vary from asphalt and cement to a variety of layered formulas involving an asphalt or cement base with a layer of padding followed by application of an acrylic coating with sand mixed in. The coating enhances appearance and provides protection from the elements. The US Open and the Australian Open use proprietary types of synthetic surfaces offering a consistently flat uniform surface. Court play is considered fast with a consistent ball bounce. Due to many and varied hard court surfaces found in tennis, the fact that these surfaces can be varied year to year and also taking into account environmental factors (i.e., weather), the shoe companies have had a difficult time adjusting their outsole materials to match these court surfaces (Personal Communication, David Sharnoff, D.P.M., 2015).

The relatively new, fast growing sport of pickleball (developed in the Seattle area) is played indoor and outdoor on a variety of hard surfaces. Pickleball is commonly played on a converted, scaled down tennis court as the pickleball court is smaller in dimension than a tennis court.

Other than the recreational "back-yard" game, badminton is classically played indoors on two types of floors, both are "sprung" floors (floors that are constructed to absorb shock and give a softer feel) with either a vinyl absorbent covering or a hardwood strip covering. Handball, squash, and racquetball are played inside on a hardwood floor (usually maple). Traditionally, handball and racquetball floors have a urethane finish, and squash has an unfinished or partially finished floor [3].

Biomechanical Demands of Racquet Sports

One common denominator in all racquet sports is the biomechanical demands on the lower extremity. A variety of foot and body movements are required involving quick changes of direction. These sudden “stop-and go” maneuvers involve specific movements depending on level of play (novice vs. advanced) and may include walking, running (forward/backward), sideward movements, hopping, jumping/landing, rotations, and stopping [5, 6]. These movements produce variable loads on the lower extremity and back that are often underestimated. For example, a tennis player who jumps up to hit a smash and lands on his/her heel (or in a “foot flat” position) may have up to six times body weight on their foot [7]. If the racquet sports player lands on their forefoot, they may have up to four times body weight on their foot [7] versus 2–3 times body weight with running [8].

One study looked at three specific factors in average versus advanced tennis players: (1) different types of motion, (2) location of foot where initial ground contact occurred, and (3) different directions of motion [6]. Various surface conditions were also considered (asphalt vs. sand/clay). The differences in average vs. advanced recreational tennis players were as follows [6]: (1) walking was the predominant movement in average players followed by running and hopping. In contrast, running occurs at the same rate as walking and hopping in advanced players. Significant sliding or sideslipping only occurred on sand (clay surfaces) and not on the hard asphalt surface tested in both groups[2]; (2) initial foot-to-ground contact occurred mainly in the heel with average players and on the forefoot with advanced players. Contact with the inner and outer shoe edges also occurred with significant frequency in both groups; (3) direction of movement is predominantly forward for average players and lateral side-to-side movement becomes more frequent in advanced players. Lateral movements were commonly combined with landing on the forefoot. In a different study looking at side-to-side movements in court sport athletes, initial landing on the rearfoot was more common than initial landing on the forefoot in an approximate 3 to 1 ratio [9]. A reasonable deduction from these studies would be that specific design features need to be considered when manufacturing a racquet shoe including the shoe/surface interface and how to best optimize foot support. Additional studies need to be performed on each individual racquet sport to validate these findings, and then apply that data to each specific sport shoe.

[2] Due to changes in the way tennis is being played in the last 10–15 years, the occurrence of sliding or sideslipping has become commonplace not just on clay surfaces but also on hard surfaces. See addendum article at the end of this chapter as author, Alex Kor, D.P.M., weighs in on this technique.

Common Injuries

In the previous edition of this chapter I sited an article that was most important at the time and remains important as a reference source for racquet sport injuries. It was a summary article regarding tennis injuries which provided a systematic literature review from 1996 to 2006 and suggested four principal findings that could be applied to all racquet sports in general [10]: (1) there is great variation in reported incidence of injuries; (2) most injuries occur in the lower extremities; (3) there are few studies that clarifies the association of risk factors and injuries, and (4) there are no randomized controlled trials investigating injury prevention measures. Though limited to tennis this article provided the basis for most of our knowledge about racquet sports at the time.

This author feels that studies in the future must clearly include the following: clarification of athlete type being studied (recreational vs. elite/professional players), player's gender (male vs. female), player's age (juniors, adult, or seniors), when injury occurred (match play vs. practice), whether player could continue to play or had to "retire" (quit playing the match), surface being played on, shoes worn, foot types of injured players, and history of previous injury. This additional information would be valuable as it may influence management and prevention protocols for common injuries.

After reviewing the world literature on epidemiology of injuries involving racquet sports since 2007, it becomes readily apparent that articles we can refer to for practical information about racquet sport injuries come from articles written on tennis and badminton. There is one article written on squash injuries from 1981 [11] and no articles on American handball, racquetball, or pickleball. Pertinent articles on tennis and badminton are highlighted below and these underscore the improved study quality and reporting of injuries which we can expect in the future.

Tennis

In a recent article authored by Pluim related to the evolution and impact of science in tennis (2014), Injury Surveillance is discussed as one of eight greatest advances for performance and health for tennis players [12]. Pluim states that though our general knowledge of racquet sport injuries has increased over the years, the reported incidence, severity, and nature of injuries show great variation between studies. Though some variation can be explained by different sample populations and conditions, the main reasons are related to significant variation in injury definition and the disparate methodologies used. To address this issue, the International Tennis Federation facilitated a meeting of 11 experts from 7 countries. The result was a consensus statement that was published in 2009 on suggested definitions and methodologies for recording injuries and illnesses [13]. This consensus should provide consistency in injury reporting for future studies and this standardized protocol can be applied to all racquet sports.

The first study that has used this standardized injury reporting system was completed in 2012 and recently published in 2014—this excellent study provides data on injury trends during a 16-year period in elite-level, professional tennis players involved in match play exposure at the US Open [14]. Some of the results were as follows: injury rates were higher during competition vs. training/practice, acute injuries were greater than gradual-onset injuries, muscle/tendon injuries predominated in both acute and chronic injury categories and were higher in men than women, rate of injury greater in lower extremity vs. upper limb and trunk, most common injury sites were ankle, wrist, knee, foot/toe, and shoulder/clavicle.

There were two studies that produced three papers related to junior tennis players [15, 16] with the following conclusions: overuse injuries predominate; overall injury incidence for boys was 1.7/1000 h and girls was 0.6/1000 h (acute injury incidence was 1.2/1000 h); ankle sprains, low back pain, and knee injuries were most common; playing more than 6 h/week was risk factor for back pain; previous injury is risk factor for reinjury and in one study average practice time was 9.9 h/week with 2.2 h of match play. From the results of these studies it was concluded that early focus on preventive measures with particular focus on monitoring and workload management is warranted.

Concerning "retirements" (unable to continue, must quit play) from match competition, there has been a threefold increase since the mid-1980s [17]. There are two recent articles written on this specific topic in professional tennis players. One article tracked health issues in Davis Cup play over a 7-year period [18] and the other tracked health issues in all tournaments conducted by the Association of Tennis Professionals (ATP) and the Women's Tennis Association (WTA) with the exception of the "majors" (Australian Open, French Open, Wimbledon, and US Open) over an 11-year period [19]. Conclusions for Davis Cup study were as follows: overall retirement incidence was 1.66%, injury rate was 6.05/1000 playing hours and 6.64/1000 match exposures, acute injuries more common in lower extremity (thigh and groin strains) and overuse injuries (shoulder and wrist tendinopathies) more common in upper extremity, more injuries on hard court surfaces, elite tennis is considered a low-risk sport. ATP/WTA study conclusions were as follows: injuries were main reason for departure, women have more "retirements" due to injury then men, lower limb injury predominates, the back is main reason for men and the thigh main reason for women, women more injured on hard courts, trunk injuries more common on grass for women and clay for men.

Badminton

There was one notable prospective study on the epidemiology of 275 badminton injuries following elite and recreational players for one season [20]. The study provided the following information: injury incidence was 2.9 injuries/player/1000 badminton hours, men were more injured than women, 58% of injuries were located in the lower extremity, injury incidence was highest in training, 75% of injuries were overuse and 25% were acute/traumatic with higher incidence of overuse injuries in elite vs. recreational players.

Another article focused on acute badminton injuries encountered over a 4-year period in an emergency department in Sweden [21]. 90.7% of cases occurred in recreational players with half the cases considered minor and the other half significant and requiring medical care. The lower extremities were affected in 92.3% of cases with Achilles ruptures, ankle sprains, and ankle fractures being most frequent. At follow-up, 52.6% of players still had symptoms and 39.5% had not returned to playing badminton.

Another study followed a group of youth players (13–16 years old) prospectively over 1 year [22]. Acute soft tissue sprains and strains were the commonest injury with 1/3 of injuries occurring in the lower limb with knee injuries being predominant. Injury risk was 57%; injury rate was 0.9 injuries/player/1000 training hours.

There were two studies that looked at injuries in elite badminton players, one study from Malaysia [23] and the other from Hong Kong [24]. Both studies were retrospective reviews. In the Malaysian study: 58.8% of injuries occurred in players <20 years of age, majority of injuries occurred during practice sessions, overuse injury predominated, majority of injuries occurred in lower extremity. In the Hong Kong study: overall injury rate was 5.04/1000 player hours, elite senior athletes had higher incidence of recurrent injury while elite juniors had a higher incidence of new acute injury, history of previous injury was significantly associated with incidence of new injury, most new injuries were sprains and strains.

Based on the author's clinical experience treating racquet sport athletes and additional literature review on injury patterns in racquet sports [24–31], most common overuse injuries encountered include Achilles and patellar tendinopathy, plantar fasciitis, stress fractures, and posterior tibial and peroneal tendinopathy. Ankle sprains, Achilles ruptures, muscle strains, subungual hematomas, and blisters are the most common acute injuries likely to be encountered.

The following injuries interestingly incorporate a specific racquet sport into their name: two specific unique ball SITE (sports-induced targetoid erythema (TE)) cutaneous injuries occur in racquet sports due to being stuck by a racquetball or squash ball: racquetball-associated TE (RATE) and TE associated with squash (TEAS) [32], tennis toe (subungual hematoma), tennis heel (intradermal bleeding), tennis fracture (fifth metatarsal base avulsion), and tennis leg (gastrocnemius myotendinous junction muscle strain). Though these injuries have been associated with a specific racquet sport, their incidence is unknown. In the author's experience, tennis leg is encountered frequently in racquet sports and is probably the most common muscle strain encountered in the lower extremity.

Racquet Shoe Design

Shoes for racquet sports can be considered part of a broader category of athletic shoes, that being court shoes. The foundation for present design of court shoes and athletic leisure footwear in general is based on the venerable sneaker which is perhaps the most significant design of all sports shoes. The sneaker has its roots in the

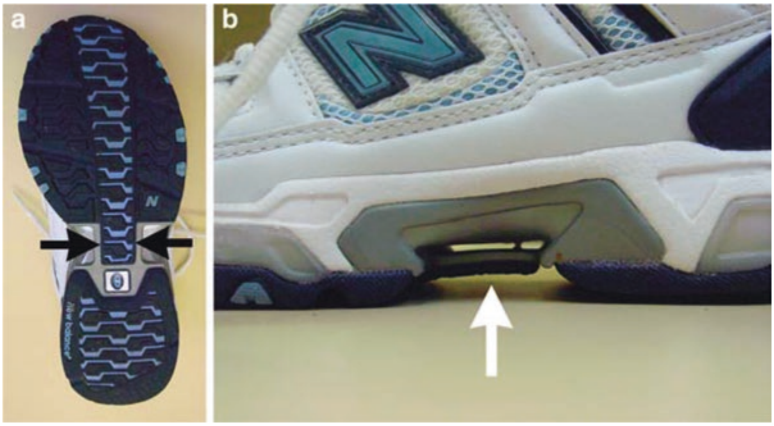

Fig. 23.1 Unique desirable design of a cross training shoe (rarely found in court shoes) with stiff, thin, longitudinally oriented outsole strut that provides sagittal plane midfoot/shank stability (*upper picture—black arrows*) but allows frontal plane torsional flexibility (*lower picture—white arrow*)

Industrial Revolution and is of simple design, with a canvas upper and a rubber outsole. The earliest British version of the sneaker was the Plimsoll or sand shoe (1876) [33] and the earliest American version of the sneaker was Keds (1917), the first mass marketed athletic shoe [34]. The first racquet sports shoe was designed by Adidas for tennis in 1931 [34].

Influenced by continued emphasis on fitness, popularity of racquet sports, injury patterns, and limited scientific research, court shoes have evolved from the basic canvas and rubber sneaker to highly technical, necessary pieces of equipment. A recent paper discusses the three most important functional design features for sport shoes, that being **injury prevention, performance, and comfort** [5]. This is in contrast to the nonfunctional design features of sports shoes (i.e., design, style, price).

Injury Prevention

For injury prevention in court shoe design, shoes should: be ***generically stable*** to counter excessive pronation and especially excessive supination involving sideward cutting movements, the latter of which is common to court sports; ***allow adequate cushion*** in forefoot and rearfoot; provide ***midfoot flexibility in the frontal plane*** to allow uncoupling of forefoot on rearfoot as players are commonly on their forefoot; maintain ***moderate sagittal plane stiffness*** in the midfoot or shank of the shoe[3] (see Fig. 23.1); strive for "***ideal" traction*** to avoid extremes of slipping versus foot

[3] In the shoe's midfoot, an ideal racquet shoe design combination would be frontal plane flexibility and sagittal plane stiffness. This combination is not found in court shoes at the present time but I have seen this feature in some cross training shoes (see Fig. 23.1). When shoes have "shank support" they are stiff in both frontal and sagittal planes and this is not ideal as uncoupling of the foot is restricted in the frontal plane.

fixation/"blocking," both of which can result in injury [5]. Toe-drag protection is also a desirable design feature for tennis shoes specifically.

To reduce risk of injury from excessive supinatory motion, shoes with high/high-mid top quarter height and firm heel counters may help (unfortunately tennis shoes only come in a low-top models), in addition to external devices such as ankle bracing. To be effective in reducing injury, these features must reduce inversion moments immediately after touchdown as shoe inversion takes place within 40 ms after touchdown [9]. Ironically, being barefoot is more stable than when wearing a shoe; the shoe sole increases the lever arm to impart an external inversion moment on the subtalar joint [9] (see Fig. 23.2). Shoe sole stability is dependent on hardness, thickness, and torsional stiffness of the sole and therefore shoes which have softer soles of mild to moderate thickness, have torsional flexibility (frontal plane), and allow heel deformation of shoe sole medially and laterally may be best [9]. Excessive slipping of the foot inside the shoe has also been recognized as a potential problem for lateral instability and strategies to address this must be considered [9] including avoiding sockliners, insoles, and orthoses with slippery top covers. The shoe/surface interface (traction) plays a significant role in injury prevention and shoe choice. One study on tennis surfaces underscores this fact as most lower extremity injuries occurred on surfaces with high translational traction (asphalt, concrete, etc.) with few injuries on surfaces with low translational traction (grass, clay, etc.) [6]. The author feels that foot fixation/"blocking" is a major factor in the mechanism for ankle sprains and other injuries in the racquet sport enthusiast. In addition, increased rotational traction has been anecdotally associated with overload injuries; therefore rotational resistance should be minimized [5].

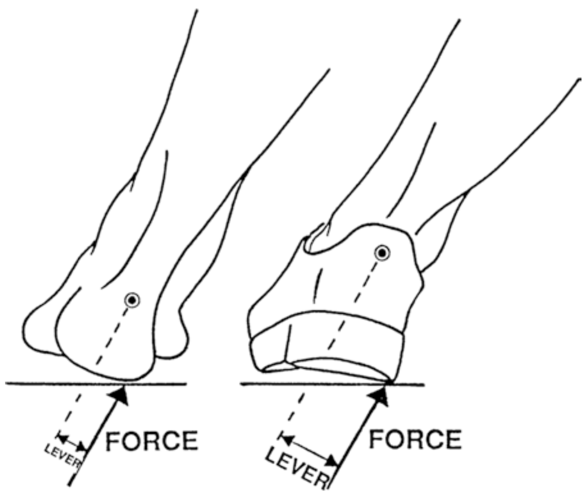

Fig. 23.2 Sideward (*lateral*) cutting movements barefoot (*left*) and with a shoe (*right*). The shoe sole imparts a greater external inversion moment on subtalar joint than when barefoot

Performance

Optimum ***traction and minimizing energy loss*** are factors that need to be considered for performance [5]. Matching shoe sole composition (solid rubber, gum rubber, ethyl vinyl acetate (EVA), polyurethane, etc.) and tread pattern [5, 35] (configuration, depth, orientation, etc.) to specific playing surfaces is the goal to prevent excessive sliding and/or foot fixation. Note: Due to many and varied hard court surfaces found in tennis, the shoe companies have had a difficult time adjusting their outsole materials to match these court surfaces (Personal Communication, David Sharnoff, D.P.M.).

From a performance perspective, players are willing to sacrifice injury prevention for increased traction which is a factor that must be considered. In many of the racquet sports (racquetball, squash, and handball) gum rubber has been traditionally used as the outsole material of choice. When used on a finished hardwood floor, translational traction of gum rubber is high due to an increased coefficient of friction which results in problems with "foot fixation." This increases the potential for ankle sprains and other injuries. The importance of tread patterns is underscored when appreciating specific tread patterns that are used for certain tennis court surfaces such as grass and clay. Grass courts mandate use of a "nub" outsole design (see Fig. 23.3) whereas clay courts require a wide channeled herringbone outsole design (Personal Communication, David Sharnoff, D.P.M.).

Energy aspects of sports shoes include two issues: how to ***maximize energy return*** and ***minimize energy loss*** [36]. The influence energy return of sports shoes has on performance is probably minimal with one study finding a 30% loss of energy input with shoe midsole materials and poor timing, frequency, location, and direction of returned energy [36]. Minimizing energy loss appears to be a more realistic focus. This can be achieved by *reducing shoe weight* (lighter the shoe, less energy expended),

Fig. 23.3 Special "nub" outsoles on tennis shoes designed to increase traction on grass court surface

using appropriate cushioned materials to minimize soft tissue vibrations (decreases need for muscle dampening), *stabilizing the ankle* (limits need for internal muscle stabilization), and *increasing midsole bending stiffness* at the metatarsophalangeal joints (improves running economy and jumping ability [36, 37]. Note: Concerning the issue of lighter shoes, this has been a significant issue especially in tennis as the shoes have become substantially lighter at the expense of stability and support. This has resulted in a higher rate of elite professional tennis players having to use ankle braces and foot orthoses to enhance their shoes stability and support (Personal Communication, David Sharnoff, D.P.M.).

Comfort

The final functional design feature for sport shoes is comfort. Although this is the most important initial factor to consider when purchasing a shoe, there are few studies available that have addressed this issue [5, 38, 39]. If a sport shoe is not comfortable, it can never truly function the way it was intended. Comfort factors to consider include fit, climate control, and various mechanical variables including skeletal alignment (heel eversion—more discomfort), torsional stiffness (stiffer—more discomfort), and cushioning [5, 37] (less cushion—more discomfort). Comfort is not exclusive, as it can influence the other design features, injury prevention, and performance. An example of this is the positive role of internal heel counters which are used to control excessive rearfoot pronation/supination as well as improve shock absorbency of heel. This feature has been touted to prevent injury and improve performance as well as provide comfort [39].

Appropriate fit is paramount to achieving comfort in a shoe. Four phases of proper shoe fit include evaluation at rest (static), standing (weightbearing), while performing activity (functional), and after activity taking into account foot swelling [40]. Matching the athlete's foot to the appropriate shoe is based on the external shoe last (form or shape on which the shoe is manufactured) and proper sizing. Court shoe external lasts are usually inflared to a variable degree with straight lasts being less commonly found. Proper sizing is dependent on length, width, and volume of the foot. For court sports, toe box shape, depth, and construction are paramount as well. Proper ventilation is dependent on hosiery used and a variety of breathable upper and insole materials presently available.

One other important shoe feature that can affect injury prevention, performance, and comfort and is commonly overlooked is location of the ***toe break or flex point.*** This area should correspond to the metatarsophalangeal joint region of the forefoot where the toes flex. It is important the toe break or flex point of shoe matches the ball of foot where the toes flex.

The aforementioned discussion has focused on comfort factors that one needs to be aware of. But how does one measure comfort and how does determination of comfort affect injury prevention, performance, and shoewear choices? Michael Kinchington, a podiatrist from Sydney, Australia, submitted his thesis for his doctorate in philosophy on this very topic publishing a series of peer-review articles in the process [41–45]. He developed and studied a Lower Limb Comfort Index (LLCI) applying it to three different groups ("codes") of footballers (Australian Rules, Rugby League, Rugby Union) [41–43]. The LLCI encompassed five anatomical areas (foot, ankle, calf/Achilles, shin, and knee plus footwear). Each area was ranked by the player on a regular basis (e.g., weekly) on a scale of 0–6 with 0 being extremely uncomfortable and six being no discomfort [41]. Dr. Kinchington concluded that this index is a reliable instrument to record lower extremity comfort in a football environment but could be applied to other sports as well [42]. A coordinated footwear management program based on comfort guidelines proved to be beneficial for injury management [44]. Poor lower extremity comfort was highly correlated to injury and was also utilized as a predictor of injury [43]. This concept has relevance for future use in sports medicine, research, and clinical practice. High comfort scores can be interpreted to be a protective mechanism for lower extremity injury.

Desirable Features of a Court Shoe

There are specific features recommended for racquet sport shoes based on current court shoe design and research (see Table 23.1). In addition to general shoe inspection (make sure heel of shoe is straight (perpendicular to ground) and lined up well while shoe is on a flat supporting surface), there are four simple tests that can be used for evaluation of court shoes: (1) midfoot sagittal plane stability (shank stability)—bend shoe and appreciate stiffness in midfoot. It should be firm; (2) midfoot frontal plane flexibility—twist shoe as if wringing a towel. There should be good

Table 23.1 Desirable features of court shoe

–	Durable outsole and tread pattern matched to surface
–	Plantar sole sub first MTPJ reinforcement
–	Full-length midsole cushion, especially forefoot
–	Sagittal plane midfoot stiffness (shank stability)
–	Frontal plane midfoot flexibility
–	Stable forefoot, midfoot, rearfoot, ankle
	Forefoot—footframe support (midsole/outsole) w/"wrap-around" construction, medial and lateral flanges
	Midfoot—nylon quarter support straps, stable tongue construction, external spats
	Rearfoot—rounded outsole w/narrow heel; low heel height with recessed (low-to-ground) construction; firm heel counter w/reinforcement; stable top-line construction
	Ankle—mid-high or high-top preferred though rarely available in a tennis shoe
–	Variable width lacing system (with laces properly tied)
–	Rubber toe cap/bumper for "toe drag" in tennis
–	Anti-shear, removable sockliner
–	Round/circular/squared toe box with ample width/depth
–	Breathable upper
–	Lightweight (for tennis shoes ideal weight per shoe is 13.5 ounces for men and 11.5 ounces for women—Personal Communication, David G. Sharnoff, D.P.M., 2015)
–	Ability to fit insole, arch support, orthoses

flexibility (not too stiff); (3) rearfoot stability—grasp and squeeze heel counter. It should be stiff and firm; (4) upper stability of forefoot—put your hand inside forefoot area of shoe, splay out your hand and move it back and forth in transverse plane. The shoe upper should be firm and not extend over the midsole/outsole. If shoe meets these criteria, it should be an acceptable shoe and likely a reasonable choice.

Orthoses

It is the author's opinion that many court shoes available today are poorly designed and are generally disappointing in that many of the desirable features are missing. Due to this situation, the role of over-the-counter (OTC) and custom orthoses have been critical in enhancing ability of shoes to prevent injury, enhance comfort, and increase performance potential. One notable example is use of orthoses to address the generalized lack of midfoot or shank stability found in most court shoes. An orthoses can provide this needed shank stability. Another factor to consider is lack of pronation/supination stability as court shoe design is usually generic and not specific to excessive pronators or supinators as many running shoes are. Custom fabricated orthoses can complement a generic court shoe to address excessive pronatory/supinatory problems and impact loading issues. A new paradigm has been introduced to explain the efficacy of orthoses based on muscle tuning and preferred joint movement pathways [46]. These new paradigms challenge the conventional thinking on impact loading and skeletal alignment, respectively [46]. Specific recommendations for court shoe orthoses fabrication can be helpful (see Table 23.2).

Summary

This chapter has provided a succinct overview of important factors to consider when recommending court shoes and orthoses for racquet sports. It is important to appreciate the uniqueness of each specific racquet sport, demands on the lower extremity,

Table 23.2 Recommended features for court shoe orthoses

–	Balanced/contoured/compressible (3.0–3.5 mm thick) polypropylene shell
–	Extra deep heel seat
–	Mild to moderate medial arch
–	Maximum lateral arch
–	Full-length, perforated, fine cell, medium soft, polyethylene foam (Ucolite®) top cover
–	For excessive supinator consider other features to exert eversion moment on foot (i.e., lateral forefoot and/or rearfoot valgus wedge, extended lateral rearfoot post[a])
–	For excessive pronator consider other features to exert inversion moment on foot (i.e., medial forefoot and/or rearfoot varus wedge, rearfoot post[a])

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[a]Heel post (or cants) should be low profile

common injuries, subject specific anatomy (e.g., foot type), shoe/surface interface issues, desirable features for court shoes, and orthoses. Further study and research is needed on individual racquet sports to determine if these shoe and orthoses features truly prevent injury, enhance performance, and provide comfort as anticipated.

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24 Football

Bruce Williams and Lowell Weil Jr.

Introduction

Football injuries are a regular occurrence no matter what level an athlete participates.

Injuries in football are associated with many complex factors, such as the position that an athlete plays, the athlete's age, their muscle tightness, and joint flexibility. Football injuries are also affected by things such as the weather, field conditions, equipment such as shoes, and the interaction of the shoe itself to the surface played upon [1–6].

The cleat patterns of football shoes and their relationship to the type of surface they are used upon have been blamed for all types of lower extremity injuries, from toe sprains and metatarsal fractures, to mid-foot and ankle injuries, to shin splints and knee injuries as well. Often the shoe-surface interface is to blame, but indeed the construction and overall stiffness and function of the shoes themselves, as well as the overall cleat pattern, can affect lower limb injuries of many types [3–14].

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Cleat Patterns and Type/Traction of Cleats and Surface Types

What relationship, if any, do cleat patterns have to rotational traction and potential injury in football? Translational traction is needed for players to run fast and to start and stop quickly. Rotational traction is necessary for turning or pivoting and quickly changing direction. An increase in rotational traction can lead to an increased rate of injury and any increase in translational traction, forward and backward movements, tends to have less overall risk of injury [9, 13].

One of the first large studies on football cleat design and Anterior Cruciate Ligament (ACL) rupture risks, done over a 3-year period, was published in 1996. This was done with high school athletes using four different types of football shoes. They found that shoes with longer cleats at the edge of the shoe were associated with higher risk of ACL rupture [8].

The authors demonstrated that increased rotational traction can lead to "foot fixation," which they found to be a common factor in ACL injuries and also with other ankle and knee injuries. High frictional forces between the cleat and the playing surface result in this foot fixation and may be partially responsible for knee ligament injuries. The athletes that are injured the most, 80% of the time, are defensive backs, linebackers, wide receivers, and running backs. All of these players do a lot of plant and cut maneuvers when playing their positions making them more susceptible to these injuries.

Axial loads can be up to six times body weight when an athlete plants and cuts.

"Cleat-catching"—occurs mainly in grass, when a cleat becomes "caught" or "dug into" the natural grass and may lead to increased frictional and rotational forces in that area where the shoe is caught. "Crow-hopping"—seen usually on artificial turf, occurs when a turf shoe hits a peak load limit and then suddenly releases in a hopping motion [12, 14]. These types of shoe-surface effects can cause an increase in shear, braking, or rotational forces along with friction resistance. All of these forces, combined with the cutting motions of football, can result in valgus and axial moments that can be transmitted proximally and lead to injury at the foot, ankle, and knee [12–14].

A study looked at the association of lower limb injuries versus soccer shoe design. The authors determined that sports-medical teams need to make sure that players are wearing appropriate shoes according to a player's individual physiology and specific position played [15]. The authors seemed to imply that if this is done that it should decrease certain risk factors for injury. Traction in footwear is good up to a point. Beyond that beneficial point, though, the risk of injury to the athlete increases incrementally [9, 13].

The effect of weather and the playing surface in relation to football shoes can also affect the risk of injury [16]. A study examined studded cleats and pressure loading patterns during cutting maneuvers on both natural grass and artificial turf with in-fill. On turf, higher central forefoot and lesser toe pressures were noted vs. grass surfaces. In contrast, with grass there were higher medial forefoot and lateral mid-foot pressures. The authors noted that this has something to do with the "Cleat-Catch" mechanism mentioned above [12, 14]. This has been shown statistically to occur with deeper cleats or studs catching on grass and leading to a higher incidence of ACL injuries in the Australian Football League [15].

A study on soccer cleats looked at the plantar pressures of amateur soccer players wearing both bladed and studded soccer cleats on artificial turf. The players performed a straight run and a run cutting at a 60° angle. They found that bladed cleats showed higher pressures under the lateral aspect of the foot and studded cleats showed higher pressures on the medial aspect of the foot. The center of pressure in the shoes with the studded cleats mimicked more normal shoe pressures much more than the shoes with bladed cleats. These results indicate that bladed cleats could predispose athletes to lateral metatarsal fracture risk [6, 17].

Another study comparing five types of rugby shoes on natural grass surface measured stiffness and peak torque of the shoes [17]. These shoes were then compared to studies of soccer shoes that were previously published in the literature. The authors found that the rugby shoes tended to be stiffer than the soccer shoes [17]. They determined that in the shoes studied there was a higher peak rotational stiffness in the shoes with “the longest studs and a small tip diameter.” The authors apparently felt this specific cleat configuration allowed for deeper penetration of the stud into the ground and likely would lead to more rotational traction and increased torque. The authors also commented that a shoe with more stiffness would likely bother players who moved and cut faster than other players who did not participate in much movement [17].

Frictional resistance between the cleat and the surface of play is nonlinear in regard to actual or physiological conditions [11]. According to this study, most shoes are tested in a lab and not under true physiological conditions. The authors felt this makes a huge difference in the testing results. They suggested taking the shoe manufacturers suggestions as to how the shoe will function “with a grain of salt.” To be safe, using a lower friction cleat type would be suggested for athletes returning from injuries until they are fully recovered. The specific arrangement of cleats on the sole of the shoe does not seem to make much difference in rotational traction. Suffice to say, any shoe that is said to give an increase in traction for cutting is likely a high-risk shoe for injury at the ankle and knee [14]. In general, shoes making these claims would likely have deeper and larger clusters of studs or spikes at the plantar shoe edges, versus a shoe with low translational traction, more likely to have larger clusters of studs that are much more shallow and rounded, i.e., turf shoes or cleats [14]. One study showed that turf cleats have the lowest torque, or rotational traction, of all tested football shoes [9].

On a contradictory note, another study comparing several different types of soccer shoes worn by professional soccer players had the players run straight ahead and do a sidestep cutting technique at both 30° and 60°. The researchers tracked knee internal tibia axial and valgus moments, anterior joint forces, and flexion angles. Ultimately their conclusion was that there were no differences in forces measured between types of soccer shoes worn. They did feel that it is more the cutting maneuvers themselves that lend risk to knee injuries, with less influence overall from the shoes themselves [6].

Finally, the NFL, FIFA, and the governing body of Rugby all do testing on shoes to determine rotational traction [12]. Unfortunately these numbers are not released to teams or medical staffs. For the well-being of these leagues and their players, this practice needs to change. Important research results such as these should be shared so that players, teams, and medical staffs can inform their players on what may be best for them depending on the weather and type of turf. Research like this can substantially help reduce injuries.

High Vs. Mid Vs. Low Top Shoes and Ankle Sprains

How does the upper construction of a football shoe affect its function in relation to injuries? In respect to rotational stiffness (previously discussed), shoes that had the highest degree of stiffness were shoes with a combination of both a very stiff sole and upper. According to two studies on shoes using cadaveric feet and legs [18, 19], football shoes with more flexible uppers are less likely to be involved in injuries to ankle ligaments vs. a shoe with a more rigid upper. The authors in both studies evaluated cadaveric ankle/foot complexes and put high and low-top football shoes on the study specimens. They then externally rotated the ankle/foot complex to test the upper flexibility and likelihood of injury. They noted that [18, 19] medial ankle injuries occurred in five of six stiff shoes vs. three of six in the flexible shoes. Ankle syndesmotic injuries were seen in five of six stiff shoes tests vs. four of six tests in flexible shoes. There were also combination injuries of both the syndesmosis and medial ankle ligaments; however only one of six of the tests in flexible shoes had a combination of both, while five of six stiff shoe tests showed a combination injury pattern. Bone injuries occurred more often in those specimens tested with stiff shoes and less in flexible shoes. Ultimately the authors feel that there may be fewer ankle injuries in shoes with a more flexible upper compared to a shoe with a stiff upper [18, 19].

In another study looking at stiffness issue in shoes [9], one of the shoes tested had a very pliable upper and also had a much lower rotational stiffness at the sole or cleat area of the shoe. Surprisingly the authors found that this still allowed for rotational traction even after the shoe had reached its breakaway point, the point where the shoe released from the field surface [9]. The authors felt that this type of shoe may allow for a lower incidence of overall injury in athletes who perform cutting maneuvers, while still allowing for good translational and rotational traction and decreasing both ankle and knee injury risks.

Finally a study looked at comfort of football shoes according to athletes [19]. The authors found that athletes rated the high-top cleats lowest because they were considered to be uncomfortable and heavy. The mid- and high-top cleats were deemed most stable by the athletes in the study. The overall conclusion of the authors was that ankle motions can be limited by high-top cleats without negating performance. Unfortunately, the athletes did not rate the heavier, more stable cleats as favorably as the lighter mid-top and low-top cleats indicating that the athletes themselves may choose a shoe that is more likely to contribute to an injury [19].

Torsion and Stiffness Issues of Football/Cleats and Use of Carbon Foot Plates

The final shoe component to discuss is the segmental and overall stiffness of the sole of football cleats, also known as LBS, or longitudinal bending stiffness. The stiffness of the sole of football shoes is vitally important when considering injury risk. Often stiffer shoes are sought out by certain playing positions to protect against injuries such as turf toe. Quicker cutting athletes have been suggested to prefer less stiff shoes [20]. Regardless of preference, the LBS of the shoe, if too stiff, can affect injury risk above the level of the foot.

A study comparing landing mechanics of running shoes, bladed soccer cleats, and soccer turf shoes found that increased sole stiffness, LBS, in bladed soccer cleats may affect the need for increased plantarflexion and dorsiflexion of the ankle joint during landing. This, according to the authors [21], could increase the risk of injury to the Achilles tendon and should be watched carefully by the medical staff, and studied much more intensely during running and other soccer maneuvers. Another suggestion from the authors was that each athlete be screened in a much more detailed fashion for their landing mechanics according to their specific sporting conditions of play and in relation to the specific shoes to be worn for competition.

Enders et al. [20] tested shoes with low, medium, and high bending stiffness in a 25 min simulation of a game. They were measuring heart rate, oxygen consumption, ventilation, and rate of energy expenditure. They found that the medium and low bending stiffness shoes had much lower heart rate and rate of energy expenditure vs. the high bending stiffness shoes. Also they found much lower oxygen consumption and energy cost vs. the much stiffer shoe, also finding that the stiffest shoes were rated as being more uncomfortable vs. the other shoes.

Stiffness in football shoes can also be increased via carbon or steel foot beds. These are often used to protect athletes after injuries such as turf toe or metatarsal fractures. Stiffness in athletic shoes in general is often studied via the addition of carbon foot beds, which can uniformly increase the overall stiffness of the sole of the shoe for repeatable study. One study using a Nike Free Shoe with carbon fiber full length plates of two different thicknesses, 1.9 mm and 3.2 mm respectively, to increase stiffness [22] and after reviewing the results, the authors found that this increase in stiffness greatly affected ankle joint moments. It essentially showed increased impulse forces transmitted up the foot and leg by attempting to overcome the increased LBS of the carbon fiber plates used in the shoe.

Another study tested jumping and landing in a regular running shoe and the same with a full-length, carbon graphite plate [22]. They found that plantar loading did not decrease with the use of the plate with either jumping or landing. This paper was testing whether increased sole stiffness would reduce stress under the fifth metatarsal so that an athlete can return to play sooner after injury. They found that jumping increases the plantar forces and force time integral under the fifth metatarsal and that landing does not decrease either of those in comparison to just wearing the shoe alone. Essentially, using a full-length graphite plates is very unlikely to be protective alone at reducing forces in a shoe along the area of the lateral forefoot [22]. This study did find that forces were reduced under the medial forefoot when jumping, but not when landing. This does imply a protective mechanism for turf toe injuries [22].

In the testing of a crossover technique and 45° cutting technique with and without a carbon fiber plate, the authors found that the plantar loading under the lateral forefoot did not reduce. They conclude that this is not protective of the fifth metatarsal and other options need to be considered. There appeared to have been no direct effect, positive or negative, at the medial forefoot in this study. Again, this may imply a protective effect from the carbon footplates when used for turf toe injuries [23].

It very much appears that LBS (longitudinal bending stiffness) of football cleats plays an important role in the risk of transmitting foot forces superiorly to the knee, ankle, or Achilles areas. Stiffer shoes can also affect overall heart rate and energy expenditure of athletes during play and may cause them to fatigue much faster. Fatigue has been shown to increase injury risk. Shoes that do not bend well or easily at the ball of the foot will likely put players at increased risk for these types of injuries and also do not appear to be protective for reducing fifth metatarsal loads. These stiffer shoes, with or without the use of carbon fiber inlays, may be protective for someone with a turf toe issue, but at what risk to a player with a knee issue or chronic ankle or Achilles issue [22].

ACL Noncontact Injuries

Anterior cruciate ligament injuries (ACL) can be devastating and potentially career ending to athletes in football. Most ACL injuries are repaired very soon after injury at the suggestion of orthopedic surgeons. The injury is most always season ending for all athletes, especially in football. Many athletes are unable to return to their previous level of play after suffering an ACL injury.

The frictional force between cleats and the field can lead to ACL injuries. We have previously discussed how rotational traction between cleats and playing surface can greatly affect the risk of ACL injuries. There is a frictional release point for all shoes on different surfaces of play. This force has been shown as a likely contributor to both contact and noncontact ACL injuries [5, 12, 13].

In studies of differing playing surfaces it appears that old-style artificial turf has the highest association of ACL injuries. While studies of professional football players playing on the new artificial turf surfaces with rubber in-fill show an association to injury, it is at a slightly lesser risk 1.68 vs. 1.92. Of all the papers evaluated in this study review [5], only one found a decrease in risk of ACL injury on synthetic playing surfaces. The majority of studies agree that the risk from artificial turf is substantial.

Different cleat types have been discussed, and their placement and depth or make of the cleats in relation to traction, cleat catching, and forces generated at the knee evaluated. These factors obviously can increase the risk of any type of knee injury, ACL included. One contradictory study found that the various football boots (soccer cleats) had no difference overall on knee loading. The authors felt that it was primarily the athletic maneuvers, or sidestep cutting that instead significantly increased the valgus and internal tibia moments and anterior knee joint forces and that is the overall problem, especially with noncontact ACL injuries [6].

Regardless of the cause of contact and non-contact-related ACL injuries, it is very apparent that the shoe-surface interface can play a large role in the risk involved to the athletes.

Cleats and Fifth Metatarsal Injuries or Metatarsal Injuries in General

Fractures of the fifth metatarsal have become a common occurrence in the NFL starting in training camp and continuing throughout the regular season. This has become a common occurrence in the soccer world as well and has been anecdotally associated with the shoes or cleats worn during competition. Fifth metatarsal fractures are suggested to happen because of cutting maneuvers and the resulting high pressures and increased bending moments of the fifth metatarsal, possibly exacerbated because of the shoes worn during play [23]. Fortunately for players who experience this injury in the NFL, the rate of return to play after injury is close to 100% [24]. This study also found that 80% of the players were still playing at the date of publication of their article in 2015. Unfortunately for many of the players studied, 12% of them had a re-fracture of the same bone subsequent to resumption of activities. This brings us to the question of whether or not football cleats may contribute to fifth metatarsal injury or injury to lesser metatarsals as well.

It has been found that straight line or translational accelerations produce higher fifth metatarsal head pressures than with cutting [23]. The authors of that study feel it could be related to overuse leading to stress fracture or actual fracture. They concluded that specific sports movements such as cutting, jumping, and landing will load the plantar aspect of the foot more than straight line running. They also think cushioning of the shoes can have an effect on plantar pressures and stress injuries from overuse. They used a football cleat and a turf shoe for the shoes studied. The turf shoe had lower peak pressures with all the studied movements and the authors concluded it therefore likely had better cushioning. They also felt that the mechanical load on the tissues was less in the turf shoe than the cleat. Finally, they postulated that a difference in the outsole stiffness of the turf shoe might have led to a better lateral forefoot cushioning, but they cautioned that they needed more data to really make that determination. This was discussed previously in relation to LBS and has been shown to increase loads in that fifth metatarsal area [22].

A study compared different types of cleats, bladed-cleat, turf-cleat, and running shoes with women and men to determine plantar loading characteristics during jumping and landing. They found that overall the bladed-cleat had an increased forefoot loading vs. the other shoes tested, and they felt the risk for forefoot injuries may be higher in this shoe. The authors felt that athletes coming back from stress fracture injury really need to be careful in choosing shoes for play because of these findings [25].

In a study between genders, men have been found to have higher lateral forefoot pressures in shoes vs. women and that this might be a reason to have gender specific shoe difference for protection in certain sports with higher risk of fifth metatarsal stress fracture [26].

When looking at different types of feet or arch heights it has been found that low arched feet can be at higher risk for increase pressures in certain athletic tasks, leading to an increased risk in metatarsal stress fracture risk [25, 27]. Low arched individuals had higher medial and lateral pressures than normal arched individuals. Normal arched individuals were found to be at less risk compared to the low arch risk individuals. Another study on walking and running pressures in low and normal arched individuals found differently, stating that there was less pressure in the lateral column in flat-footed study participants. This may indicate less risk of fifth metatarsal stress fracture in lower arched athletes [28]. Finally, the literature suggests that those with high arched feet are at increased risk for fifth metatarsal stress fractures [25, 27].

In this author's experience with in-shoe pressure mapping the general suggestions of these studies appear to be valid. We would caution that every athlete is different and that segmental structure and function, especially in stiffness, plays a role in these findings and risks for injury. Callus formation under the fifth metatarsal phalangeal joint could indicate prolonged pressures in this area and increased stiffness. Either could indicate increased risk for the athlete in terms of fracture at the lateral column.

Cleats and Turf Toe Injuries

Turf toe is usually considered a hyperextension injury of the first metatarsal phalangeal joint, first MPJ, and generally involves injury to the plantar capsule, muscles, and sesamoid structures. A study [29] was done on 44 players from one NFL team, 13 of whom had a history of turf toe injury in college or their professional career. The authors found that passive dorsiflexion of the first MPJ was significantly decreased in those with a history of turf toe injury vs. those who had not been injured this way. They also found that peak hallux pressures were higher in the athletes with injury and, when adjusted for Body Mass Index, BMI, the relationship was significantly higher ($p = 0.0003$) in those with previous injury. The first MPJ pressures tended to be lower in injured athletes as well, and as an anecdotal reference, this author can confirm seeing this relationship repeatedly in all types of patients with any type of hallux limitus, functional or structural, or history of first MPJ injury [29].

George et al. [30] show that there are less than 1% of team turf toe injuries per year for teams in the NCAA. The artificial surface is more likely to be the contributing factor to the injury rather than grass, though less than with old first generation artificial turf. Shoes do play a role, and taping and stiffening the shoes can be protective. Ford et al. [3] showed in-shoe pressures higher in artificial turf vs. grass with higher forces in the medial and central forefoot on artificial turf.

Aranda et al. [31] link plantar fasciitis with lower hallux dorsiflexion range of motion. This could play a role in football players with increased stiffness in the forefoot of their shoes being more prone to plantar fasciitis and related problems.

The use of carbon or steel plates in football to protect the foot after turf toe injury is very common. We have shown previously that this may decrease pressures in the medial aspect of the foot [22, 29]. This may allow for protection at the turf toe in these shoes. Do keep in mind that increase LBS can increase the load at the heel, ankle, Achilles tendon, and the knee [21, 32].

These are huge risks for players, indicating the stiffness of the shoes, depending on the position that the athlete plays, really needs to be thoughtfully considered. Overall we would not suggest an across the board use of shoes with increased MPJ stiffness in football shoes. If an athlete has a chronic risk of this type of injury turf toe, and minimal risk at other areas where motion can be translated, i.e., the ankle or knee, then it is something that can be considered. It must always be kept in mind that if other compensations, soreness, swelling, or specific injury arise while wearing any protective foot plate or overly stiff shoe, that the shoe or plate must be considered as a source of the new problem.

In Conclusion

Football cleats and shoes have been shown to have a significant effect contributing to many types of lower extremity injury. While the specific pattern of cleats has not been shown to affect injury, the type of cleat and depth that it can penetrate the playing surface has. Torsional traction has been associated with injuries ranging from ankle sprains to ACL and other knee injuries. It appears that shoes with less torsional traction translate to a much lower risk of injury, especially regarding turf shoes. Translational traction is associated in part to injuries of the fifth metatarsal. The overall stiffness of the upper of the cleats/shoes has been shown to affect torsional injuries of the ankle, with shoes/cleats with much more pliable uppers being associated with less risk of ankle injury, and more overall comfort in players. While low-top shoes appear to be more comfortable to athletes, increased protection can be afforded from mid- and high-top cleats/shoes. The playing surface affects risk of injury as well, with some indication that artificial turf can be related to an increase in overall injury in football. Finally, the LBS of the shoe, when increased, can be protective of turf toe injuries, but can also lend risk to injury at other more proximal joints such as the ankle, achilles, and knee complexes.

It is imperative that the medical team, coaches, parents, and even athletes pay much more attention to what football shoes are being worn during play. While shoes themselves are not always to blame for injuries in a high velocity contact sport like football, their risks have obviously been shown and it is up to us all to assist the players in making good choices for their overall risk and history of injury. As a final note, in order to play it safe across the board, it would make sense to wear a turf or rounded and low depth studded cleat for play that has a pliable upper, and pliable LBS.

Best of luck in your selections!

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25 Skating

R. Neil Humble

Skating in all its various forms has shown increased popularity worldwide. Olympic speed skating champions are coming from areas of warm climate and ice hockey teams are starting up in almost every populated geographical location. There are three major types of ice skating: hockey skating, figure skating, and speed skating. All these forms of ice skating have similarities and differences with respect to footwear and biomechanics. A close cousin to the three major types of ice skating is in-line skating. This is a similar biomechanical activity and an increasingly common recreational and fitness endeavor.

Management of all the various forms of skating with respect to both performance and injury reduction involves discussion of footwear. In general, all footwear functions to both improve performance and to lessen the likelihood of injury. Skate boots also do this and depending on the demands of the type of skating being done the boot type and structure can change dramatically.

All skate boots function firstly to help protect the foot from acute external traumatic events, secondly to protect the foot within the boot by adding internal comfort, and lastly to assist in performance-based outcomes and biomechanics of the sport.

Hockey Skate Boots

Anatomically there are three main parts of a hockey skate boot: the boot itself, the blade housing, and the blade, Fig. 25.1. Firstly, the skate boot itself is generally rigid for protection and support. As with most athletic footwear the lasts vary from one manufacturer to another. Other than a good fit, one must carefully look at the

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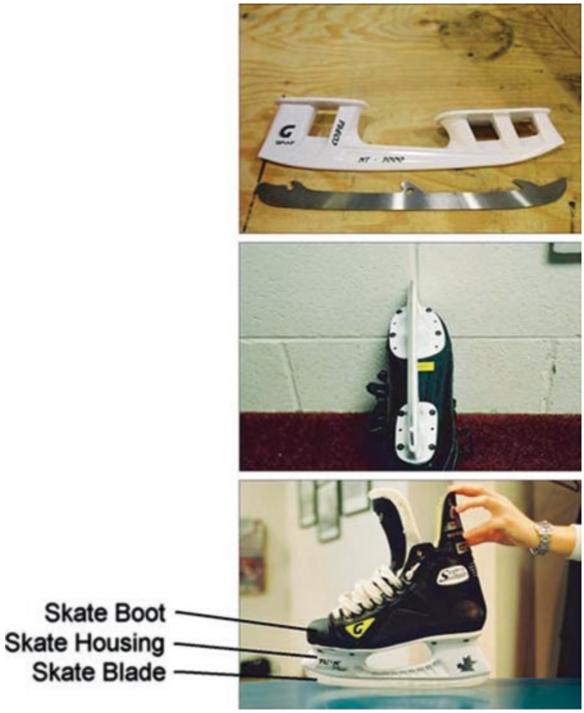

Fig. 25.1 Skate anatomy

pitch of the boot from heel to toe, which can vary from 5° to 9° and affect forward lean. With respect to lasts the heel fit is the most important single-fitting point. Boots can be stretched and adjusted in the forefoot, but if the heel does not fit well and without slippage, adjustments are difficult. The fit of a skate is slightly different than that for regular shoes. Sewn skates generally fit one to one and a half size smaller than one's regular shoe size. Skates need to fit snugly and toes should "feather" the toe cap. Interior in the boot is the liner of the heel counter. This portion of the boot is usually made with heat-moldable materials, to allow for individual player differences and thus comfort adaptations. Also on the interior of the boot is a removable insole under which lies the skate blade housing rivets.

The exterior of skates was traditionally leather, but gradually has been substituted with synthetic materials. Graphite and polypropylene materials have been added for strength and protection of the boot with flex points added to allow proper ankle joint plantarflexion in the skating motion. The toe cap is always rigid for toe protection.

The next part of a skate is the skate blade housing. This portion of the skate is riveted or screwed onto the boot itself. The attachment of the blade housing to the boot can be a point of biomechanical input. This housing can be moved medial to lateral, or anterior to posterior on the boot. Its standard position is to hold the blade centrally under the heel and then to continue forward under the second metatarsal head and further forward through the second digit. The blade housing can also act

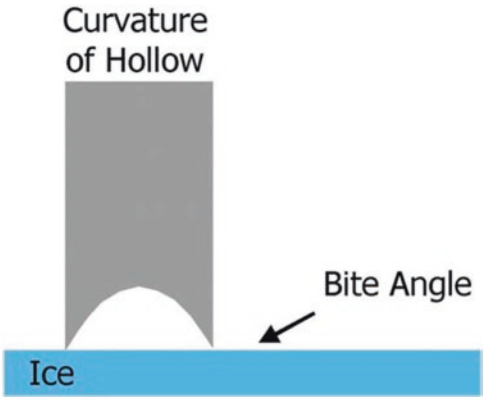

Fig. 25.2 Frontal plane blade-ice contact; surface is hollow ground along its length

as an attachment site for heel lifts and wedges as they are sandwiched between the housing and boot. The portion of the rivet inside the boot can be a potential source of irritation.

The last anatomical portion of a skate is the narrow skate blade itself. This portion of the skate is traditionally made of stainless steel and is a necessity given the surface of the activity but can be adjusted in many ways for specific biomechanical effect. It is rockered front to back and can be varied for desired performance. The rocker acts as a balance point with as little as 1 in. contacting the ice. A longer radius of curvature allows for more blade to contact the ice and thus can improve balance and speed. A shorter radius of curvature increases the ease of turning and improves maneuverability. The bottom surface of the blade is hollow ground to create a medial and lateral edge or bite angle, Fig. 25.2. This curvature of hollow can be altered at the time of sharpening to get a desired bite into the ice. The technology in skate blades is ever changing. One newer technology is disposable titanium blades that can be purchased with varying degrees of rocker and with varying curvatures of hollow. These blades stay sharper longer than traditional stainless steel blades and can be easily removed and replaced when worn out or damaged. An even more recent advancement in blade manufacturing is the ability to buy blades with varying bite angles. These blades are presently being tested to prove their expected capability to increase speed and turning ability.

Goalie Skates

Goaltender skates are similar to player skates, with some obvious differences specific to the requirements of the position, Fig. 25.3. The boot itself does not go as high up the lower leg as traditional skate boots. This is primarily due to the need for increased ankle mobility in this position. Also, the skate blade housing encompasses the entire lower portion of the boot to create a plastic housing of protection for the foot.

Fig. 25.3 Goalie skates

Fig. 25.4 In-line skates

The blade has a longer radius of curvature to help improve balance, as well as a wider width to avoid breakage. All the same adjustments that can done in a player's hockey skate can also be done on a goalie skate.

In-Line Skates

Two major components differentiate in-line skates from traditional hockey skates. The most obvious is that instead of a blade, wheels are attached due to the difference in sport surface. Just like skate blades can be changed for rocker and material, so can the types and sizes of wheels be altered. The second major structural difference is the ventilation systems used to accommodate heat transfer as most in-line skating is done in a warmer environment than traditional ice skating, Fig. 25.4.

Figure Skates

The design of figure skates as we know them today has changed very little in over a century. The biggest changes, like those seen in hockey skates, are with construction materials. Figure skating boots are designed to provide the foot and ankle with the stability necessary to perform difficult jumps and spins; however, this rigidity brings with it a myriad of lower extremity problems and injuries. The figure skate blades vary in that there are “picks” at the anterior end of the blade to help with function and maneuverability, and the radius of curvature is longer than that of a traditional hockey skate blade.

Since 1990 the actual art of skating figures, also known as compulsories, has been eliminated from the sport, and has been replaced with increased emphasis on free skating, which includes jumps, spins, lifts, and throws [1]. The stiffness of skate boots has long been linked to lower extremity injuries in figure skating, and the increased amount of time spent practicing jumps may result in a greater frequency and degree of severity of these injuries [2]. Skaters may perform 50–100 jumps per day, 6–7 days a week, and the force generated from a typical skating jump amounts to eight to ten times the skater’s body weight [3]. Because the design of figure skates allows for very little flexion at the ankle, skaters land on their heels, and since the hardness of the ice surface offers almost no shock absorption, most of the force is transferred to the knees, hips, and spine. Most figure skating injuries involve the lower extremity, and many are directly related to the skating boot [4].

Figure skating is the only jumping sport that confines the movement of the ankle joint and calf muscles by the use of rigid boot support [5]. The skate boot is designed with a high heel and inflexible ankle portion that limits ankle plantar flexion, which decreases effectiveness in jump takeoff and restricts the ability of the ankle to cushion the landing [5]. The force absorbed by the knee extensor apparatus contributes to occurrence of patellofemoral pain and various overuse injuries. In a study by Dubravic-Simunjak et al., 42.8% of female and 45.5% of male singles skaters reported overuse syndromes, the most frequent injuries in females being stress fractures and jumper’s knee in males.

Not only does the design of figure skate boots cause injuries, but poor fit can also lead to deformities of the foot. In an article for the US Figure Skating website, Linda Tremain reports that up to 57% of skaters have bunions, while 31% have enlarged navicular bones, likely related to uncorrected pronation problems of the boot and blade or the foot itself. She also found that excess heel slippage has led to the development of Haglund’s deformities in 49% of skaters, and hammertoes in 18%. Current research and trials are under way to design an articulated boot that may decrease the magnitude of landing forces by allowing more sagittal plane mobility while still providing the stability required to execute difficult jumps and spins [6].

Speed Skates

In contrast to the unchanged design of figure skates, speed skates have undergone radical changes in the past decade, which have brought about tremendous improvements in both world record and personal best times.

Conventional speed skates featured a low boot with a long, thin blade that was fixed to the boot. A skater would push off until the leg was fully extended, at which point the ankle would naturally want to plantar flex and continue the push. However, this would cause the toe of a conventional skate to dig into the ice, called "toeing off," which hinders the gliding motion [7]. To prevent the tip of the blade from scratching the ice, speed skaters had to use a technique where plantar flexion was largely suppressed during push-off. This limits the efficiency of the stroke because the ankle plantar flexors are prevented from contributing to the push, which also restricts the work done by the calf muscles and knee extensors and causes the skater to lose contact with the ice before the knee is completely extended [8]. Speed skaters often suffered from pain in the tibialis anterior due to this forced suppression on plantar flexion [7].

The clap skate was introduced in 1997 which features a hinge under the ball of the foot that allows the ankle to plantar flex at the end of push off while the blade continues to make contact with the ice. Skating velocity increased by 5% and mean power output improved by 10% due to an increase in both stroke frequency and work per stroke [9]. Surprisingly, this improvement is not simply due to the ability of the ankle to extend at push-off, but rather the difference in the center of rotation between the foot and the ice surface [10]. With conventional speed skates, the foot is turned into a long lever because it must rotate around the tip of the skate blade, which is located approximately 10 cm in front of the toes [10]. This extreme frontal location of the center of rotation creates an ineffective push-off and makes it difficult to set the foot into motion. The hinge of a clap skate allows the foot to rotate around the ball of the foot, which greatly enhances the effectiveness of plantar flexion in the final phase of push-off, leading to increased gross efficiency and mechanical power output [9].

The hinge must be located under the ball of the foot to achieve optimal performance; however, the exact position varies from skater to skater depending upon his or her build and skating technique [10]. Determining the most advantageous location for the hinge is still a question of feel.

Understanding basic skate boot construction along with an understanding of the biomechanics of the sport can assist in making functional interventions in both performance and comfort.

Biomechanics

All the various forms of skating along with the associated footwear are somewhat different. However, the basics of motion, push, and glide are similar as is the performance surface. So for discussion purposes regarding biomechanics we will discuss the biomechanics of power skating.

Power skating in hockey involves skating forward and backward and with multiple directional changes as the game evolves. It is this ever-changing movement pattern that makes this activity difficult to study from a biomechanical standpoint. It is forward acceleration and striding, however, that are the most consistent and studied aspects of power skating and a commonality that is seen with other forms of skating. The understanding of foot and lower extremity balance on top of a narrow balance point, the skate blade, will allow a practitioner to assist in both improved performance and overuse injury patterns.

In order to better understand the biomechanics of power skating and the clinical injury perspectives that may arise, it is first helpful to compare power skating with the more commonly understood biomechanics of walking. Both walking and skating are biphasic movement patterns that consist of periods of single- and double-limb support. By comparison, it is the support phase of walking that becomes the skating glide. One aspect of skating that makes it unique in the support phase is that the friction on the performance surface is much less than that seen in most walking activities. As a result there are decreased posterior linear shear forces with touch-down due to decreased friction and decreased anterior linear shear forces in the late midstance to propulsion stage. This low-friction surface will necessarily impart a need to abduct the foot by external hip rotation at propulsion [11]. The center of gravity therefore does not progress in a linear sinusoidal path over the foot as seen in walking, but rather the skater and his or her center of gravity move in an opposite direction to the weight-bearing skate.

The acceleration in power skating is divided into two unique stride patterns, the first three strides and the fourth stride, known as the typical skate cut [12].

The first stride pattern usually involves the first three strides. It lasts approximately 1.75 s, involves continual positive acceleration, and has a negligible or non-existent glide phase [13]. It is during this stride pattern that the skater often appears to be “running” on his or her skates.

The second stride pattern often begins on the fourth stride and is considered the typical skate cut [12]. This stride pattern consists of periods of positive and negative acceleration and involves three phases. It starts with a glide during single-limb support which imparts negative acceleration [14]. It continues with propulsion during single-limb support which is accomplished by external rotation of the thigh and the initial extension movements of the hip and knee [15]. This stride pattern concludes with propulsion during double-limb support. During this phase the second limb acts as a balance point to complete propulsion through full knee extension, hyperextension of hip, and plantar flexion of the ankle.

Clinical Injury Perspective

From a footwear and biomechanical perspective there is firstly the intrinsic foot-to-boot injuries that can be precipitated from the nature of the unique footwear, and secondly, there are the specific biomechanically produced clinical injury patterns that may arise from overuse.

Biomechanically produced overuse foot and ankle clinical injury patterns can clearly be identified in ice skating. The narrow blade or balance point creates a need for strenuous eccentric muscle control and proprioceptive skills to assist in balance over this small balance point. As a result, general foot fatigue from strain of the small intrinsic muscles of the foot is common. As well as the intrinsic muscle strains, there are the extrinsic tendinopathies that can occur in the posterior tibial tendon and the peroneal tendons and muscles as a reaction to the need for balance.

In comparison to other sporting activities, power skating shows a decrease in the number of contact-phase injuries due to he low friction of the ice surface. The overuse injuries in the lower extremity usually show up more proximally in the groin or low back due to the inherent need for skate and skater to be moving in opposite directions as propulsion occurs. Groin injuries in the adductor muscle group (adductor magnus, longus, and brevis) occur when the thigh is externally rotated and the hip is abducted, thus putting this muscle group under maximal strain. Dr. Eric Babins from the University of Calgary has reported a reduction in pain of the lumbar spine and lower extremity along with improved performance with proper fitting of skates, blade alignment, and adjustment for leg length discrepancies as required due to the improved biomechanical balance above the skate blade.

Clinical Biomechanical Balance

There are two steps in the process to assist a skater from a biomechanical perspective. The first is the positioning of the foot within the boot using standard podiatric biomechanical principles. The second is the balance of the blade onto the boot itself.

Step 1: Foot Balance Within Boot-Custom Foot Orthosis

A general podiatric clinician can be confident when dealing with the first step of biomechanical control, which is positioning the foot properly within the boot. A complete lower extremity and foot exam needs to be done as would be done for any athletic population, and a decision on foot orthoses can be made using sound root biomechanical techniques [16]. These techniques of forefoot to rearfoot and rearfoot to leg control will help to compensate for biomechanical faults, help stabilize the subtalar and midtarsal joints, and help maintain sound structural alignment of the lower extremity from the midtarsal joint to the hip, providing a solid lever for propulsion. This orthosis can then be improved upon by using a general understanding of skating mechanics and applying the newer techniques of foot orthosis control as discussed by Kirby and Blake [17, 18].

As a skater is in single-limb support in the early stages of propulsion, the foot is abducted and the hip externally rotated. The skate and skater are moving in opposite directions at this time while trying to balance on the narrow skate blade. As such, the center of gravity is much more medial with respect to the weight-bearing extremity, and even subtle biomechanical faults, causing excessive foot pronation, will cause a skater to spend too much time on the medial skate edge. Power and efficiency are created by staying on the outside edge as long as possible early in the typical skate cut. Therefore, maximally controlling the medial column of the foot with respect to the subtalar joint axis location can greatly assist a skater with this

Fig. 25.5 Skate orthosis

task. Using both the newer positive cast modifications of medial heel skive and inversion techniques along with traditional biomechanical controlling techniques improves skating power and balance during propulsion.

A typical custom foot orthosis design for skating would include the following features; see Fig. 25.5:

1. Neutral suspension casts of feet [16]
2. Trace or send skate insoles with casts to improve boot fit
3. Intrinsic forefoot posting unless custom extra-depth skate boots are used
4. Standardly, invert casts 10° using Blake technique to increase medial arch contact and to increase time spent on lateral blade edge: increase as clinically justified
5. Standardly, use a 3–4 mm medial heel skive cast modification to help with lateral edge control: increase as clinically justified
6. Polypropylene shells are preferable as they be more easily modified as needed to the medial shank of the skate boot
7. Extrinsic rearfoot posts work if well skived to fit in the heel counter of the boot and when used with a thin cap to decrease heel lift: there should be no motion allowed within the rearfoot posting
8. Use full-length extensions with thin top cover materials of good friction next to the foot for grip and "feel": a thin layer of firm Korex under the extension will protect the forefoot from irritation from the blade housing mounting rivets in the boot
9. Some skaters like buttress or toe crest pads built into the extension for their toes to grip onto

Step 2: Blade Balance

The second step in mechanically helping skaters involves blade balance. Blade balance is accomplished using three different techniques: sagittal plane rocker, medial-lateral position of blade, and varus/valgus wedging of blade, which can incorporate limb lifts. These interventions are usually best performed by a professional skate mechanic after medical advice is given.

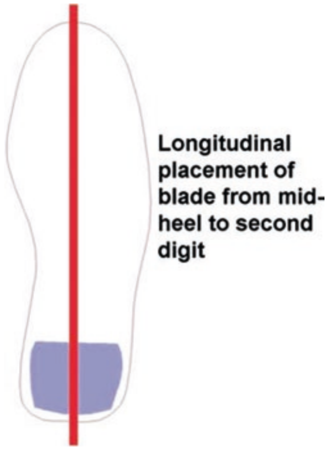

Fig. 25.6 Standard blade placement

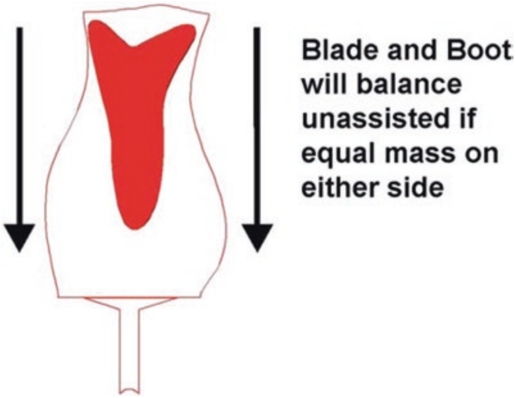

Fig. 25.7 Standard blade placement, posterior view

The sagittal plane rocker of the blade allows for easy response to the center of gravity changes in the sagittal plane. Standardly, the rocker is in the center of the blade with only 1 in. of the blade in contact with the ice. Some skaters will increase their rocker (decrease contact with ice) in order to improve their maneuverability. Others will decrease their rocker to allow more blade to contact the ice and this will increase speed but decrease turning capabilities. Adjustments of rockers are more a matter of individual preference for performance, and should only be done in the hands of a skilled skate technician.

The medial-lateral position of the blade on the boot has a significant effect on a skater's posture and balance. The standard blade placement is longitudinally from heel center to the second metatarsal head, and second digit. This blade position should provide an inherently stable platform for the foot to sit with only pure sagittal plane rocking; see Figs. 25.6 and 25.7.

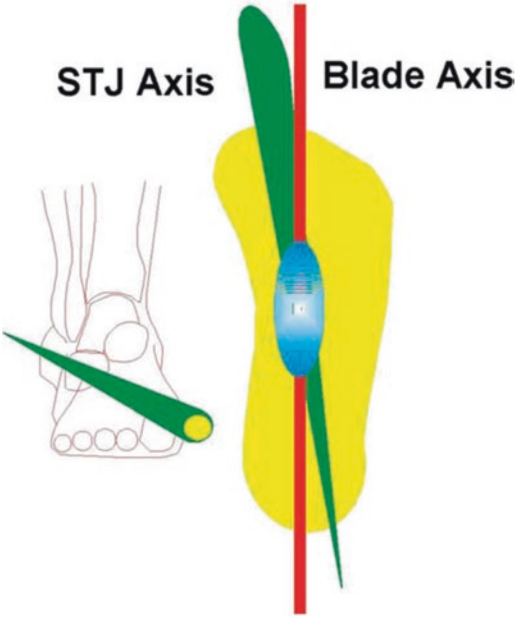

Fig. 25.8 Standard blade placement compared to subtalar joint axis

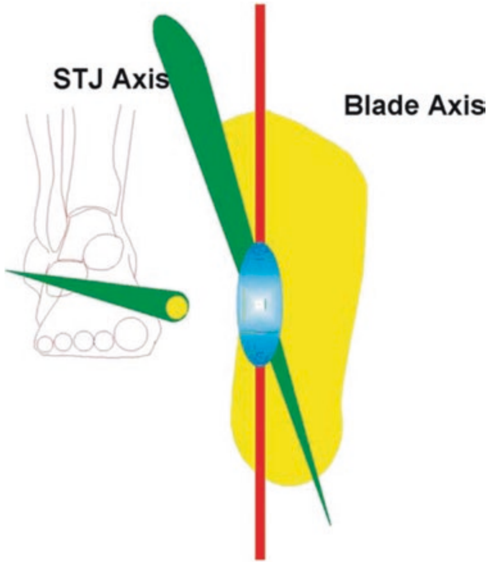

Fig. 25.9 Shifting blade medial may put it in a more functional position

A medially deviated subtalar joint axis will influence the default contact portion of the standardly placed blade. Shifting the blade medially in this circumstance will place the default contact portion of the blade in a more functional position with respect to the medially deviated axis in those patients. See Figs. 25.8 and 25.9. In extremely rigid inverted feet, moving the blade laterally on the boot will help to improve balance.

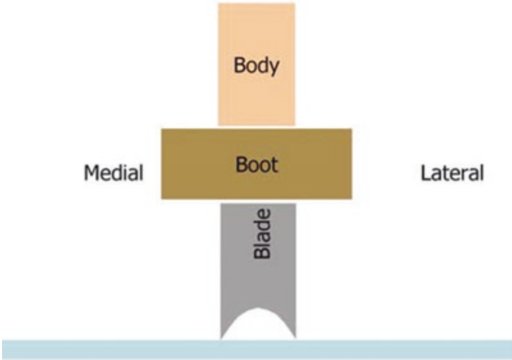

Fig. 25.10 No wedge needed

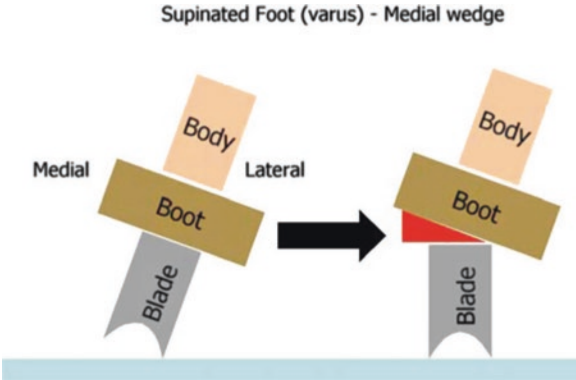

Fig. 25.11 Supinated foot, or lower extremity varum-medial wedge

Balancing the blade with wedging is the final blade adjustment technique. After an appropriate orthosis has been made, the rocker has been checked, the blade has been moved medially or laterally as needed, and a decision on using a wedge can be made by looking at the position of the blade edges with respect to the weight-bearing surface. A wedge can assist in balancing the blade to the boot and upper body so that in static stance each edge of the blade balances on the ice surface equally. As odd as it may seem, a supinated or varus foot can require a medial wedge to bring the medial blade edge evenly to the ground. A pronated or valgus foot can require a lateral wedge to bring the lateral blade edge to the ground; see Figs. 25.10, 25.11, and 25.12.

The podiatric management of the skater can be best shown through a series of case examples. Each of these scenarios depicts the management of increasingly complex cases involving both foot-to-boot balance and blade-to-boot balancing techniques.

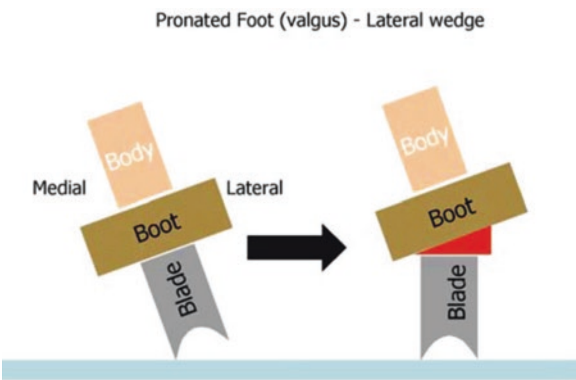

Fig. 25.12 Pronated foot, or lower extremity valgum-lateral wedge

Fig. 25.13 Case number 1, moderate pronation

Case #1: Moderate Pronation

Ten-year-old white male suffers from medial arch and heel pain predominantly in his day-to-day activities, which carries over into his recreational hockey, Fig. 25.13. He is otherwise fit and healthy and has been diagnosed with plantar fasciitis.

A complete podiatric biomechanical exam was performed and the pertinent results were a 2° forefoot varus and a 4° forefoot supinatus bilaterally, Fig. 25.14.

The first goal in treatment was a daily orthotic to relieve his symptoms and the secondary goal was a skating-specific orthosis to improve his skating performance and his enjoyment of his recreation. The polypropylene skating orthosis was made from a neutral suspension cast with reduction of the supinatus. The forefoot was first posted intrinsically 2° varus and then the casts were modified with 10° of inversion and a 3 mm medial heel skive. A rearfoot post was added to balance the orthosis. A functional skate orthosis with maximal control was used to assist this patient, along with a good-quality and well-fitted skate boot, Fig. 25.15. No blade adjustments were needed, and the blade was left in its standard default position.

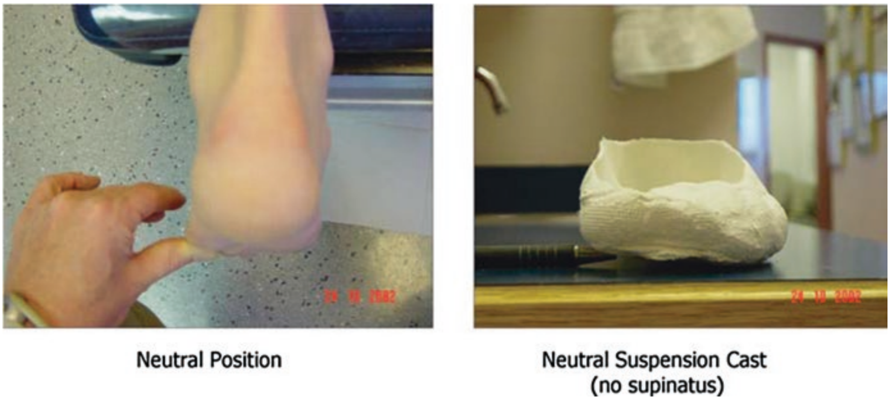

Fig. 25.14 Case number 1, moderate pronation

Fig. 25.15 Case number 1, moderate pronation, quality skate, and custom foot orthotic

Case #2: Moderate-Severe Pronation

Twelve-year-old male suffers from medial ankle and knee pain while playing hockey. He is otherwise fit and healthy. After a complete history and physical examination, a diagnosis of posterior tibial tendon strain and patellofemoral pain syndrome was made. The primary etiology of his problems was deemed to be biomechanically produced strain from excessive foot pronation, Fig. 25.16. He functions maximally pronated due to a fully compensated forefoot and rearfoot varus deformity bilaterally of approximately 4° for both.

A custom foot orthosis was manufactured from casts corrected to 25° of inversion using the Blake inversion technique and a 4 mm medial heel skive was added. The forefoot to rearfoot was posted a further 4° of varus and a balancing post was placed on the rearfoot also in 4° of varus, Fig. 25.17. A further mechanical intervention was needed to improve balance, and the blades were moved medially on the skates, Fig. 25.18.

Fig. 25.16 Case number 2, moderate-severe pronation

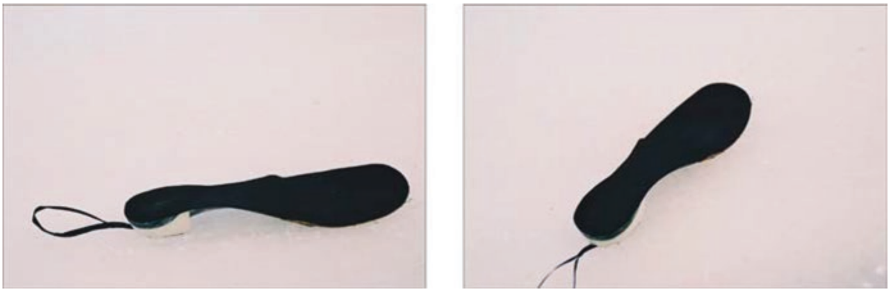

Fig. 25.17 Case number 2, skate orthosis

The final solution for this patient was a good-quality skate boot appropriately fitted, an aggressive custom foot orthotic, and a blade balancing adjustment, Fig. 25.19.

Case #3: Supinated Pes Cavus Foot Type

An 18-year-old Western Canadian Hockey League player suffers from lateral leg and ankle pain, as well as skate balance problems. History and physical exam finds him otherwise fit and healthy. A diagnosis of peroneal tendonitis was made secondary to a rigid forefoot valgus and a limb-length discrepancy, Figs. 25.20 and 25.21.

Fig. 25.18 Case number 2, blade adjustment

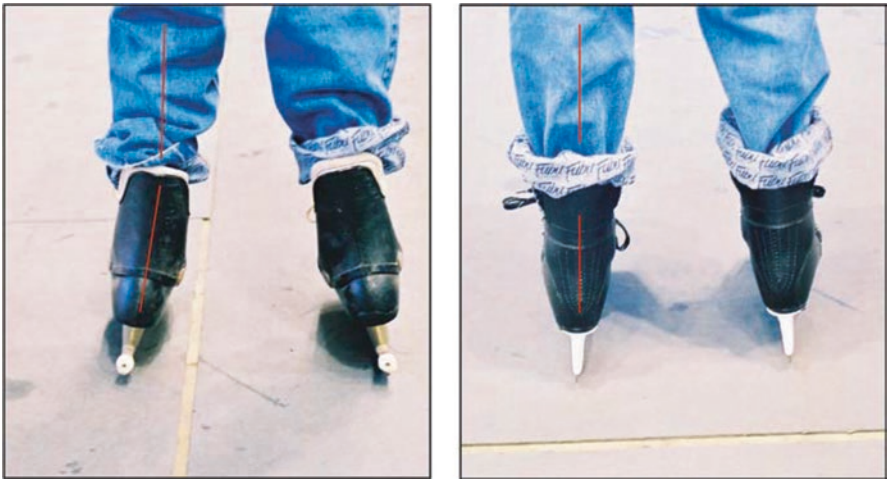

Fig. 25.19 Case number 2, end result

Fig. 25.20 Case number 3, pes cavus with forefoot valgus

Fig. 25.21 Case number 3, neutral cast

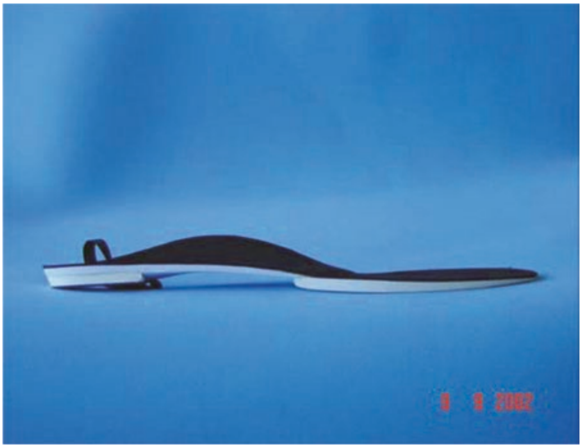

Fig. 25.22 Case number 3, skate orthosis

The mechanical solution to this patient's problem was a custom-made, extra-depth skate boot to accommodate an orthotic with an extrinsic forefoot valgus post to the sulcus. Standard root biomechanical principles were used to make this orthosis and no newer inversion techniques were utilized, Fig. 25.22.

Many blade adjustments were needed to assist in this patient's performance. A limb lift was added full length, the blades were moved laterally on the boots, and a medial wedge was inserted to assist further in bringing the medial edge of the skate blade down to the ground.

Conclusion

Skating in all its various forms is showing increased popularity throughout North America. All foot care practitioners can expect to see ice skaters in their offices. A sound understanding of the footwear used in these sports along with the use of proven podiatric biomechanical management techniques as used in other athletic populations can assist the practitioner in assisting with the pleasure and performance of this unique activity.

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Skiing and Snowboarding

26

Jeffrey A. Ross

Downhill Skiing

Alpine or downhill skiing is a complex skill that requires a series of integrated movements that requires controlled pronation, setting the foot, ankle, and lower extremity on the inside ski edge. Pronation sets the inside edge of the downhill (control) ski and allows for the skier to lean inward against the ski which holds a skidless arc throughout the turn. Even today with wider parabolic skis, the skier drives the shin forward against the stiff wraparound type, or hybrid type boot cuff and swings the hips to the opposite direction. The ski rolls onto its sharp steel edge and bites the snow, creating an arc across the hill [1]. Skiing in the freestyle is like ballet dance on snow, yet at the same time, the skier encounters many centrifugal and G-forces, as turns are created, while simultaneously attempting to keep the center of gravity in line over the center of the ski. Any deviation of normal lower extremity biomechanical balance can alter the skier's ability to carve a controlled turn, thus placing the skier at risk for injury if the biomechanical abnormality is great enough. Before a skier should consider taking part in this demanding sport, three important factors are important in a skier's conditioning and performance, namely flexibility, strength, and adequate range of motion of lower extremity joints. A number of variable factors such as structural deformities, functional deformity, or dynamic imbalance of muscle groups can influence the performance of the skier and also help to predict potential injury. When skiers have pre-existing injuries, i.e., knee instability, quadriceps muscle weakness, posterior tibial dysfunction, chronic peroneal tenosynovitis, etc. this will contribute to muscle weakness, decreased flexibility, and limited range of motion of involved lower leg joints. This will limit the skier's ability to ski efficiently and safely, and as a result, increase the muscular

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effort required, resulting in greater skier fatigue. Fatigue has been shown to be one of the main factors in the incidence of downhill skiing injuries [1], and the same effect occurs in snowboarders as well.

Skiers will typically compensate for structural biomechanical abnormalities through hip and knee pronatory forces in order to hold the skier's edge and to ski in proper control. Ross incorporated the electro-dynogram (EDG) to show that forces are transmitted from both the forefoot and the rearfoot, which is essential in up-and-down weighting, as well as in the completion of proper turns [2]. There were many abnormalities observed with this technology, namely excessive foot pronation, shortened heel contact and excessive propulsive phase on the toes, extreme forward lean of the boot, limb length discrepancy, including asymmetry between the 2 ft. All of these findings contribute significantly to the skier's efficiency and performance.

The use of custom footbeds and custom foot orthoses in ski boots has been shown to be effective in improving skiing style, edge control, reducing excessive pronation, and other foot imbalances. It has also been shown that custom insoles (made at the ski shop) can help control milder degrees of pronation and other lower leg imbalances (tibial varum, genu valgum). For the more severe rearfoot and forefoot abnormalities, a custom foot orthoses is valuable to provide proper footbed balance and improve ski performance and efficiency [3]. The use of easy-to-customize liners and removable full-length soft support systems has also become a integral part of the comfort and support system. Custom foot orthoses may be substituted for the pre-existing insole.

In order to work effectively with the skier, the foot specialist or sports medicine specialist must have a basic understanding of both boot design and the biomechanics of ski performance in addition to a close working relationship with the ski shop and the boot fitter/ski tech. The foot specialist can assist in the proper selection of the "right" boot, by first determining the skier's foot type, and targeting existing areas of biomechanical imbalances, protruding bony areas of the foot that lead to friction and irritation, circulatory compromise, nerve entrapments, and metabolic disorders (diabetes).

After taking these factors into consideration, the boot fitter can assist the skier in selecting a boot designed for a wide foot, a flat or high-arched foot, a foot that requires large volume, a pure forward entry boot or hybrid (with both overlap and rear-entry design), a narrow heel pocket, or with a thin, thick, or adaptable liner. Early research noted that a majority of National Ski Patrollers, ski racers, and ski instructors wear a custom footbed, insole, or custom foot orthosis in order to achieve biomechanical neutrality while improving skiing efficiency.

Once the unbalanced foot is situated in the ski boot, the bucking down of the boot can result in a significant loss in volume and can also accentuate or aggravate already existing biomechanical imbalances within the foot or lower extremity, which can lead to improper fit of the boot, overuse injury, or a resulting traumatic injury [1]. Ski boot designs change rapidly, with new designs, variations in the inner boots and shells, internal canting and buckle systems, as well as variability of forward lean (Fig. 26.1a, b).

Fig. 26.1 (**a, b**) Ski boot designs

Tibial Varum

Tibial varum is a biomechanical abnormality that can have a great deal of negative effect upon the skier's ability to ski normally [4]. Tibial varum is a result of an uncompensated varus deformity of the tibia which transmits instantaneously to the ski–snow interface and causes the skier to ride excessively on the outside edge of the ski. When a skier has more than 8–10° of tibial varum deformity, he or she will have a great deal of difficulty initiating the parallel turn without "catching" the outside edge of the ski. Skiers who chronically ski on the outside edges of their skis when attempted to "set-up" the next turn will have difficulty getting on to their inside edges, and when they do will often cross tips, which can eventually lead to sudden falls and possible injury [1]. High-performance boots of this day and age provide a boot cuff adjustment to accommodate varying degrees of tibial varum in order to create a flat ski surface. One of the simplest and most reliable means of treating tibial varum is to use a full-length, canted, in-boot foot orthosis. The advantage of this method is that the orthosis provides for total foot contact within the boot, affording the skier greater correction of lower extremity imbalances within the foot and leg. Another typical problem that can be eliminated with a balanced footbed or orthosis is the reduction of friction on bony areas of the foot against the boot, while simultaneously affording a comfortable, dependable, balanced footbed that helps to provide effectual edge control [4].

Tibial Valgum

Skiers who have tibial valgum or genu valgum of the knees will be constantly on the inside edges of their skis. The inward position of the knee sets the skier up for potential crossing the ski tips, as well as decreased control of the uphill ski. These skiers will relate that they "caught an edge" even on the flat terrain as a result of this lower leg position. In addition the skier will also complain of medial collateral ligament strain from excessive internal femoral rotation, leading to patellar tracking and patellofemoral joint syndrome pain. Tibial valgum is associated with coxa vara–genu valgum as well excessive pronation of the feet. Orthosis control will typically correct the improper knee position and allow for a more neutral position of the foot on the ski. However, when this is not sufficient the use of a cant may be necessary to provide for lower extremity alignment. The knee position can be visualized to be more frontal when the skier stands on a bench with both the orthosis and the cant in place.

Forefoot Varus

Forefoot varus imbalance can also lead to a forefoot that "rides" on the outside edge of ski, similar to a subtalar varus. When the skier stands on a platform and a vertical plumb line is dropped from the midpoint of the patella, it should drop directly down to the vicinity of the second metatarsal. However, if the line drops more laterally, forefoot varus imbalance may continue to be present. Additional forefoot posting on a full-length orthosis may be required to correct this imbalance. The skier will be able to feel the difference and relate much more stability in the forefoot. It is important not to overcorrect the rearfoot with extrinsic posting which can elevate the heel causing a potential rearfoot boot fit problem, and/or irritation at the posterior aspect of the heel. Skiers have often complained about boot fit and comfort. They often state that their feet hurt, and that they are cold, tight and irritating. Compared to years when first skiing with laced leather boots, technological advances in design and performance have made boot comfort a standard in the industry. Designs have changed over the years, having gone from the traditional overlap design, then through a rear-entry revolution and now having come full circle back to a forward entry and hybrid designed performance boot. From a biomechanical standpoint ski boots have become extremely sophisticated biomechanically. There are a number of adjustable features now on boots which include internal versus external canting systems, adjustable spoilers or shaft-angle adjustments, boot flex, forward lean, internal/external heaters, as well as custom heat-moldable liners made of ethyl vinyl acetate (EVA). To facilitate the use of custom foot orthoses, most ski boots have footbeds that easily can be removed. Most ski shops offer custom insoles that can be made readily by using computer technology or with an apparatus which places the foot in a semi-weight-bearing neutral position, with knee stabilizer apparatus built into the platform to accurately align the knee over the foot, for complete lower leg correction. The traditional prescription can either be made with computer technology and plaster casting in neutral position outside the boot or from an in-boot cast while the skier assumes a neutral ski stance position, quite often functioning which much greater control than the custom insole, due to increased correction and stability in the rearfoot, subtalar joint, midtarsal joint, and forefoot. By locking the midtarsal joint, and controlling excessive pronation/supination, we can achieve greater stability and balance which will afford the skier greater edge control and better performance. When looking at the ski boot, there are five areas of concern:

- Zone 1, the footbed
- Zone 2, the tongue
- Zone 3, the hindfoot
- Zone 4, the shaft
- Zone 5, the forefoot

Alpine skiing has become much more technical but with the advent of parabolic skis, initiating turns with advanced ski boots have made initiating turns much simpler, with much less energy exerted through the hips, knees, and lower extremities. The foot specialist must be cognizant of the various challenges which skiers have to confront. It is imperative that the specialist have a clear-cut understanding of lower extremity biomechanics related to the sport of skiing.

Snowboarding

The sport now almost 20 years old has become mainstream with youngsters and adults alike. Many adults who for years were alpine skiers and/or runners have found snowboarding to be much gentler on the knees. First began as a winter version of skateboard surfing, it has its own inherent risks as does alpine skiing. The snowboarder may find falling a common event due to an exaggerated uphill edge that is required for carving turns. Most injuries from snowboarding occur due to falls, as well as striking obstacles as in tree boarding, or from colliding with other boarders/skiers on the mountain.

Unlike alpine skiing the initiation of a turn from a snowboard takes longer and the carve of the turn takes a longer period of time. This necessitates a wider area for the turn to be accomplished. According to Ganong et al. [5] snowboarders sustain a wide variety of injuries: 44% involve the upper extremity, while 43% are from the lower extremity; 12% head, spine, or torso; and 4% miscellaneous. The most common site of injury is the wrist (trauma and fracture), followed by the knee (sprains) and the ankle (fractures). The abundance of upper extremity injuries is due to the fact that the boarder lacks the freedom of individual leg movement, which unlike alpine skiing does not allow for as quick a recovery. In snowboarding a sudden "hop" is required in order to make that instantaneous correction. Due to a sideway position of the board and the feet and torso facing forwards, when the fall occurs, the snowboarder will usually fall forward on the hands, wrists, and upper extremity. The twisting fall involved in a turn will typically involve the lower leg. Unlike downhill skiing, which uses the integration of foot, knee, and hip motion, snowboarding concentrates its energy on the hips and knees owing to the nature of the short pivoting turns [4]. Biomechanical balancing on the snowboard is equally important as it is on the alpine ski. It is essential that when the snowboarder is riding the board edge the foot be as neutral on the midsection of the board as possible.

Fig. 26.2 An example of a binding system for snowboarding

Snowboard boots have evolved over the years beginning with a soft design, followed in recent years with a full hard shell and half-shell design. Compared to the harder designs, the softer version snowboard boot allows for greater movement within, which gives the boarder the advantage of tactile sensation and proprioception on the board. However, this boot design may increase the risk of injury compared to the harder designs. Soft boot injuries will typically be seen in the ankles, whereas the more rigid full-shell boots protect the ankles, while allowing for greater forces to be transmitted to the knees. This results in an increased number of knee injuries. The binding systems for the boots have also improved (Fig. 26.2), making snowboarding safer and a higher performance winter sport.

Cross-Country Skiing

Cross-country skiing has increased in popularity over recent years as a cross-training alternative to alpine skiing, and as another exercise activity for all ages that provides an excellent cardiovascular workout. Elson reported that 1 h of cross-country skiing is equivalent to 2 h of downhill skiing, or 2–12 h of tennis, or 4 h of cycling at 5.5 miles per hour [6]. Cross-country skiing, another endurance sport, provides an excellent means of upper body as well as lower body development. Only swimming can achieve as even development of muscular groups with aerobic effects. For runners searching for a safe cross-training winter activity, cross-country skiing is excellent in cases where underdeveloped anterior muscle groups and over-developed posterior groups can be equalized.

As opposed to alpine skiing, cross-country skiing has a different technique, as well as application. In downhill skiing, the heel and lower leg are locked in a rigid boot, applying control to the foot's subtalar joint and rearfoot complex. In addition, the skis will typically rest directly beneath the body's center of mass, with a constant parallel location. Whereas in cross-country skiing the heel is repeatedly lifted from the ski surface and lowered again, allowing for a certain degree of skier imbalance. The classical technique for cross-country skiing is commonly referred to as a swing kick and glide. The poles assist in creating upper body stability and propulsion, while the heel is kicked upward to maintain forward motion, which allows forefoot propulsion on the ski. A smooth alternating gliding motion is attained with a technique referred to as the diagonal stride. By alternating the opposite arm and leg forward, a ski gait is created similar to walking and jogging [7]. Similar to running, as the skier's pace is increased, the forward lean of the body over the skis will increase. This will produce a swing-phase ski that as it touches the snow, will slide forward in a motion better known as the "glide." The opposite-sided ski, known as the stance phase ski, will press down on to the snow surface under full pressure, creating a stable platform which allows for a plant and push-off action to occur.

The velocity of the diagonal stride is affected by three factors: stride length, stride rate, and horizontal skier velocity. The distance that the skier can kick and glide is referred to as the stride length. Duoos-Asche claims that the stride length is one of the most important factors in increased skier velocity [8]. The number of kicks and glides performed in a certain time frame, known as the stride rate, will also have an influence but to a lesser degree than the stride length. The horizontal skier velocity is a total forward velocity achieved from stride length and stride rate. Among racers and those cross-country skiers who want to achieve maximum energy efficiency, achieving the greatest stride length and stride rate is the key [1].

Cross-country boots are quite different than the alpine version. They are an intermediary between back-country and racing boots in both design and support. The cross-country touring boot has a greater freedom of movement, yet sacrificing support. Because the touring skier moves predominantly in sagittal plane motion, this unidirectional sport with only moderate curves involved does not necessitate as great a stability boot. Due to the flexibility of the boot, and a lack of stability, a skier's biomechanical imbalances will be accentuated, thus creating malalignment over the skis.

Biomechanical considerations for the cross-country skier are essential. The patella should be properly aligned over the skis in a bent-knee skiing position. A lighter, more flexible orthosis, rather than the bulkier more rigid device is preferred. The device should be fabricated as thin as possible, in order to provide greater volume for the foot and toes to function [1, 4].

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Cross-Country Skiing

27

Paul R. Langer

Cross-country (XC) skiing has evolved from a centuries-old means of transportation for populations living north of the Arctic circle to a sport and fitness activity enjoyed by millions of people worldwide [1]. Development of new ski techniques, better training and teaching methods, groomed trails, and technological advancements in equipment have made this activity more accessible and popular in recent years. The number of XC skiing participants in the USA fluctuates annually in part due to snow conditions. According to the Snow Sports Participation Survey published by Snow Sports Industry America 4.1 million participants skied at least 1 day in the 2014/2015 ski season. Seventy-five percent of those skiers are skiing on groomed trails [2].

XC skiing is a metabolically more efficient movement than running and walking because of the ability to glide on the ski as well as to use the arms and poles for propulsion. Gliding reduces the metabolic cost of skiing [3, 4]. One study showed that in terms of energy cost per distance travelled, XC skiing allows participants to move at double the speed of brisk walking for the same metabolic power [1].

There are two distinct techniques or disciplines utilized in XC skiing—classic and skate. There are also other variations of XC skiing that include backcountry and telemark skiing and a sport that combines the two called ski mountaineering but the focus of this chapter is on conventional XC skiing. The ski equipment utilized will vary depending on the technique, terrain, and performance level of the skier.

The classic technique has been used for centuries and likely evolved naturally because of its similarity to walking and running [5]. Skate skiing is a much newer technique which was introduced in the 1980s. It is a more efficient and faster means of moving over the snow—at least when on a groomed track [6]. Each of these techniques has variations on the standard form which are utilized depending on

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the terrain, snow conditions, skier ability, and speed. While running and walking are bipedal gaits, the use of poles makes XC skiing a quadrupedal gait. The key differences in equipment are that classic skis are longer but the poles are shorter than for skate skiing. There are differences in the waxing methods as well.

Classic Skiing

The classic discipline utilizes what is known as a "kick-and-glide" or "diagonal stride" technique and is the most similar to walking and running [7]. See Fig. 27.1. Research indicates that the amount of propulsion provided by the poles is variable but increases with slope inclination for both classic and skate [8].

Although there is not yet a universally accepted definition of the subphases of the classic ski gait cycle according to Barberis [9], there does seem to be agreement that there are, like running and walking, two primary phases of locomotion—glide phase and kick or propulsive phase. Smith subdivided the kick phase into an "early" and "final" kick [10]. In the terminal phase of classic glide, propulsion occurs as the skier pushes with the pole while kicking off the momentarily stationary ski and then transferring weight onto the gliding contralateral ski. There is a moment of gliding as the final component of the stance phase occurs on one limb (the propulsive limb) and as the contralateral limb (the glide limb) has finished the swing phase and begins to load on the opposite side. The glide phase that follows kick occurs as the posterior arm and pole are brought forward to plant the pole in front of the skier's center of mass as the arm extends and opposite leg flexes at the knee and hip in early

Fig. 27.1 The classic XC ski discipline utilizes a kick-and-glide technique (photo credit Bruce Adelsman)

swing and then extends in terminal swing to slide the unweighted ski forward just before gliding on that limb.

Unlike skate technique which propels off of a moving ski, classic propulsion begins on a temporarily stationary ski [10]. The load on the stance limb and ski at midstance (just prior to kick) is highest at this point in the cycle and approaches 1× bodyweight [11]. This higher force allows the ski to flex and the “kick zone” or wax pocket of the ski then contacts and grips the snow in order to provide propulsion. The kick zone is an area of the ski bottom extending from the heel of the boot anteriorly 70–75 cm which is covered with a klister or grip wax which prevents the ski from sliding during propulsion [12]. The remainder of the ski—the tip and tail—are covered with a glide wax. The camber of the ski when not fully weighted allows the kick zone to lose contact with the snow while the tip and tail remain in contact to maximize forward glide.

Waxless skis use a raised fish scale type of pattern on the bottom of the ski’s kick zone which provides grip on the kick, when the ski is pushed backward and glide when the ski is moving forward. Waxless skis are preferred by recreational skiers who would rather not to have to change wax regularly to adjust for different snow conditions and temperatures. Ski racers prefer wax for its performance benefits.

Double poling is used both in classic and skate skiing on flat terrain. It consists of the skier utilizing both poles simultaneously for propulsion while the skis remain evenly weighted and parallel. Propulsion comes exclusively from the upper body in this technique.

Fig. 27.2 The freestyle or skate skiing discipline (photo credit Bruce Adelsman)

Skate Skiing

Skate skiing is also sometimes called freestyle skiing (Fig. 27.2). The skate technique is very similar to ice skating in that the power-generating phase occurs off a foot and limb that is externally rotated in relation to the plane of progression. The popularity of skate skiing is largely due to the fact that it is metabolically more efficient and skiers can attain greater speeds [6]. Skate skiing must be done on a wide, packed, groomed skate deck. Poling is done with both poles simultaneously in synchronization with propulsion from each leg as opposed to the contralateral arm/ski motion in the classic discipline. Unlike classic skiing where the skiers' center of mass (CoM) changes minimally from medial to lateral, skate skiers shift their CoM significantly as they alternate propulsion from limb to limb.

There are variations of the pole and ski timing that skate skiers will use depending on the terrain. For example, some techniques are best for conserving energy and skiing flat terrain. Other techniques expend more energy but are better for sprinting and climbing. A skate skier provides ski propulsion by first gliding on the flat ski and then pushing posterior lateral while transferring weight to the medial foot and edging the medial ski edge into the snow in the terminal propulsive phase. The skate skier pushes off the ski as it is gliding anterior and lateral. The poles provide more propulsion in skate skiing than in classic which is why the poles are longer [13].

Pursuit or Combi Skiing

Some ski racing formats combine the two disciplines of Nordic skiing in pursuit racing. In this format, racers ski a set distance in one discipline and then the second half of the race is skied in the other discipline after changing skis and poles (and boots for those who choose not to use "combi" or "pursuit" boots). The skier who was first in the first discipline starts first and the other skiers are sent out after him or her based on the amount of time they were behind after the first discipline. The field then pursues and attempts to overtake the leader. This racing format requires that skiers be proficient at both the classic and skate disciplines.

XC Skiing Injuries

Overall, XC skiing has a relatively low incidence of both overuse and acute injuries. Estimates of overall injury rates vary from 0.1 to 0.5 injuries per 1000 skier days [6, 14, 15]. The lower extremity is the most common site of both acute and overuse injuries. Interestingly, one study found that XC skiers were injured more often while doing non-ski training activities [16]. Overuse injury risk factors are similar to other sports: training errors, poor technique, and improper equipment.

Acute injuries are typically caused by falls or collisions with stationary objects and are much more common on downhills than flat or uphill sections due to increased velocity [14]. Boyle and colleagues described the most common mechanism of acute injury to the lower extremity as "an external rotation abduction moment applied to an entrapped ski." This mechanism of injury is much more common in Alpine skiing as the free heel of XC skiing bindings allows more freedom of movement of the lower extremity during a fall.

Chronic exertional compartment syndrome has a high incidence especially affecting the anterior compartment in elite skate skiers [17, 18]. High tibialis anterior muscle (TA) activation during both swing and stance phases of the ski cycle may be a mechanism of anterior compartment syndrome. It was initially speculated that the mass of the ski and boot required increased activation of the TA muscle during the swing phase and this was the most likely mechanism of injury but Federolf and Bakker's EMG study in elite skiers with anterior compartment syndrome showed that differences in TA muscle recruitment patterns were more significant during the glide phase than during the swing phase indicating that the TA was also important in balance [19]. These high-activation patterns during both the glide and swing phases of ski gait likely contribute to the high incidence of anterior exertional compartment syndrome.

Low back pain is not uncommon in both classic and skate skiing due to repetition of hip and back extension. Iliotibial band syndrome, hamstring injuries, and chondromalacia patella are more common in skate than classic as reported by Schelkun [20].

In an injury survey study done at the American Birkebeiner ski race (the largest ski marathon in North America) in 1996, foot and ankle injuries were the most common injury followed by hand/wrist injuries [15]. First metatarsal phalangeal (mtpj) joint pain has been described as more common in classic skiing than skate [20]. Classic technique requires more dorsiflexion of the first MTP joint than skate skiing due to the demand for dorsiflexion required during the terminal kick phase of the ski cycle. Individuals with first MTP joint dysfunction such as bunion deformities and or hallux rigidus or other arthritic conditions of the great toe joint may be predisposed to pain in this joint in the classic XC discipline. Skating technique, which utilizes more lateral forces from the ski and more power from the poles for propulsion, does not require as much dorsiflexion of the first MTP joint.

XC Skiing Footwear

Vogel described XC ski footwear as a combination of an Alpine ski boot and a running shoe [21]. Ski boots will have different structural features depending on whether they are intended for classic or skate disciplines. There are also hybrid boots or "combi" boots which combine structural features that are suitable for both classic and skate disciplines. Combi boots are also sometimes referred to as "pursuit" boots because pursuit racers must ski both classic and skate disciplines. Hybrid boots offer cost savings and convenience over having to buy two different boots. Other variations in boot structure are influenced by the ability of the skier and snow surface. In general, recreational skiers tend to place a higher priority on warmth and comfort while racers may be willing to sacrifice some warmth and comfort for performance features in a ski boot.

XC Ski Bindings

Boots for XC skiing provide the means for transferring power from the foot to the ski through a secure binding system. So before we discuss the boots in detail we must first discuss bindings.

Bindings have evolved from leather straps and cable devices to three-pin and to today's most commonly used bar system. While leather and cable systems have become mostly obsolete, three-pin binding systems are still utilized for Nordic backcountry skiing but both modern classic and skate use bar systems. In the bar system, a steel bar is embedded in the distal end of the boot sole and is secured into a clip on the binding. This allows for a stable attachment of the boot but also freedom of motion much like a door hinge [22]. The free heel of Nordic ski bindings allows for more power during the propulsive phase in both classic and skate disciplines as the foot can plantarflex in order to maximize power transfer to the ski. The free heel also reduces (but does not eliminate) the risk of lower extremity fracture and catastrophic knee injuries. XC bindings do not release in a fall as they do in Alpine skiing. Ski-binding manufacturers may at some point introduce bindings that release in a fall but currently there *are no such bindings on the market.*

Unlike Alpine ski equipment manufacturers, who have standardized their systems so that all boots and bindings are compatible, there are two distinct bar-binding systems for XC skiing (Fig. 27.3). New Nordic Norm (or NNN) and Salomon Nordic System (or SNS) are very similar in appearance with a grooved plastic binding plate attached to a metal clip [23]. The grooved plate articulates with matched grooves on the bottom of the boot and allows for better control of the ski especially

Fig. 27.3 NNN ski bindings and boot

at high speeds and downhills when the boot is flat on the ski. The metal clip secures the bar at the toe of the ski boot. The main difference between NNN and SNS is the geometry of the longitudinal groove(s) on the binding plate and boot bottom. NNN uses two thin parallel grooves and SNS uses one wider groove. The newest version of NNN is NIS (Nordic Integrated System) where the ski manufacturers make the ski with an attached binding plate. This system is compatible with NNN boots and allows for the proper binding placement in the ski shop by clicking the binding in place without having to drill holes. SNS also has a newer binding system that utilizes two forefoot bars for attachment which is claimed to provide better control of the ski. One bar is at the distal aspect of the boot and second is just distal to the metatarsal-phalangeal joints. There are other variations of these two binding systems and technological and design advancements will likely contribute to further changes in the future.

In determining which binding system to utilize, most ski retailers advocate first fitting the boots and, once the most comfortable and suitable pair has been selected, then matching the binding system to the boot. The rationale for this approach is that boot comfort is so important and the differences between NNN and SNS binding systems are negligible for most skiers [24].

Nordic Ski Boot Structural Features

As with any athletic footwear, the functional requirements of XC ski boots dictate their design. Nordic boots need to provide weather protection from both cold and snow, moisture management as the skier perspires, efficient energy transfer from the foot to the ski, and comfort by combining fit, cushioning, and support characteristics. These functional requirements are achieved through structural design elements and the use of different materials.

In contrast to running footwear, there is very little published biomechanical research on the topic of XC ski footwear. Much of the available information is descriptive and utilizes manufacturer's proprietary marketing terms and does not include scientific validation. In addition to boots specific to backcountry, classic, and skate there are subcategories of ski boots within each discipline. Racing, sport, recreational, offtrack, and even boots specific to roller skiing (utilized as a training method on paved surfaces in warm weather) are offered by most manufacturers. Almost all boots are made from synthetic materials and consist of a stiff sole, an outer moisture/snow-resistant shroud, and an inner wrap for a snug fit. Most ski boots now have removable insoles which make it much easier to modify or customize the boot with foot orthoses (Figs. 27.4 and 27.5).

Uppers

The upper of the Nordic ski boot has a number of jobs to do related to performance and comfort. It must fit snugly enough to minimize foot motion within the boot.

Fig. 27.4 Classic ski boot

Fig. 27.5 Skate ski boot

Excessive foot movement within the boot wastes energy and causes skin irritation. The upper must also provide weather protection especially from wind, cold, and snow. Most uppers utilize multiple materials to provide weather protection yet breathability for internal temperature and moisture management. The closure systems may use zippers, laces, hook-and-loop, cable, or ratchet buckle systems or a combination of the above to secure the boot around the foot. The uppers of more expensive boots often have heat-moldable liners and/or shells which can be customized for comfort by a skilled boot fit technician. Skate boots and racing boots incorporate stiff heel counters and ankle cuffs to provide rearfoot and ankle support. Some manufacturers offer models with canting or cuff adjustments that allow for modification to address tibial varum and tibial valgum.

The height and stiffness of the boot cuff tend to be lower for classic and higher for skating and combi. Backcountry boots may build in a gaiter or snow cuff. The most common anatomical sites for foot discomfort related to the upper in a Nordic

Fig. 27.6 Outsole of NNN ski boot bottom and SNS profile boot top (note the two bars). The outsole of the top boot is made of carbon fiber

boot are the malleoli, heel, and metatarsal-phalangeal joints 1 and 5. The upper of the boot may be low cut or have a high cuff. Skiing on groomed surfaces makes it less likely that snow may get in the boot and the more uniform density of the snow surface makes high cuffs less necessary [25]. This will be discussed in more detail in the following sections.

Outsole

The function of the outsole is to provide a secure binding fixation point and efficient energy transfer from the foot to the ski (Fig. 27.6). The outsole is made of nylon, plastic composites, or carbon fiber. The torsional and longitudinal flex is less stiff for classic and more stiff for skating. Racing and high-performance boots will be more stiff both torsionally and longitudinally than touring and recreational boots for both disciplines. Recreational boots, with their more flexible soles, can lose 5% of energy during propulsion while the stiffest racing boots lose only about 1% [21]. Because stiffer boots tend to be less comfortable, even elite ski racers may choose a more flexible boot over stiffer race boot based on their comfort preferences or previous history of foot pain or injury.

Insole

The sock liner or insole of most boots is minimally cushioned or supportive. Fortunately, it may be removed easily to allow for modification or replacement with an aftermarket insole or custom foot orthoses.

Ski Boot Last

The fit of any footwear is determined by the last or the form around which it is made. The last will dictate the fit characteristics of the boot and includes toe box shape, heel height, width, and volume. The last of recreational XC boots tends to focus more on comfort and so tends to have more volume than racing boots. Racing boots, on the other hand, prioritize performance over comfort and tend to be manufactured on "performance lasts" which have lower volume interiors. The low volume allows the manufacturer to reduce weight and provides more efficient energy transfer from the foot to the ski.

In general, racing and high-performance boots are stiffer and lighter than recreational boots. Race boots may utilize carbon fiber in place of thermoplastics for the sole, heel cup, and ankle cuff because it offers increased stiffness at a reduced weight. A study on bicycling shoes found that stiffer shoes minimize energy loss during propulsion but they are more likely to cause discomfort [26]. High-end boot options also include thermoformable heel cups and ankle cuffs which can be individually customized. Finding the "perfect" boot for any skier, whether they are an elite racer or a beginner, is a matter of balancing their unique needs and preferences for performance and comfort.

Classic Ski Boots

As mentioned previously, classic technique is primarily a movement in the sagittal plane. For that reason the boot is designed to flex at the MTP joints and does not provide ankle support or rigid external ankle stabilizers as skate boots do.

Skate Ski Boots

Both the outsole and the upper of skate boots are stiffer than classic as skating requires less metatarsal-phalangeal joint flexibility and more ankle joint complex stiffness in the frontal and transverse planes. Torsional stiffness of the outsole minimizes lost energy and allows for better edge control of the skis [27]. The external ankle cuff provides medial and lateral stiffness yet is hinged to allow for ankle dorsi- and plantarflexion. Hladnik stated that the torsional stiffness of the sole and transverse stiffness of the ankle of the boot should be as "high as possible" in order to provide optimal transfer of power [28].

Combi Boots

For skiers who prefer to have one boot for both disciplines, combi or pursuit boots are suitable. They combine some of the features required for each discipline. The outsole stiffness cannot be adjusted but the ankle cuff may be adjustable or removable to allow quick and easy transition.

Boot Fit and Comfort

XC ski boots should fit “comfortably snug.” Skiers should be fit while wearing the socks they plan to ski in. Recreational skiers often choose thicker, warmer socks than racers who may prefer thinner socks. Ski boots must be fit well in terms of the foot shape and length in order to maximize comfort and minimize pain. A boot that is too tight will cause pressure on the toes and restrict blood flow to the feet. A boot that is too loose will cause blisters, waste energy, and compromise control of the ski due to movement of the foot within the boot. Most boot fitters agree that the toes should be lightly touching the front of the boot when standing. Classic skiers should flex the boot as they would while in the kick phase of the ski cycle to ensure proper fit and skate skiers should feel light toe pressure while standing on a single leg.

Fortunately, when advising patients on selecting athletic footwear regardless of the sport, the best evidence points to focusing on comfort [29]. Miller and colleagues found that footwear comfort seems to be related to fatigue, injury development, and performance. Fit, based on foot shape, is the most important factor in comfort followed by skeletal alignment. The stiffness and cushioning of the footwear were important but still required good fit to be perceived as comfortable by test subjects [30, 31].

Comfort features of a ski boot such as cushioning and flexible soles may feel good but are less efficient in transferring energy from the foot to the ski. Conversely, performance features such as a minimal cushioning and stiffer flex allow for more efficient energy transfer but provide less comfort. Comfort is subjective and cannot be measured [32]. Athletes prioritize comfort and performance features differently, so it is best when fitting boots to allow the skier to make comparisons and then select based on their personal preferences.

Aftermarket Ski Insoles

The vast majority of research on foot orthoses is done on walking and running gait and not on skiers. Off-the-shelf insoles are marketed to XC skiers as products that can improve comfort, decrease the risk of injury, and/or improve performance. Many retailers offer both customizable insoles and standard insoles. Standard insoles can vary significantly in terms of cushioning and stiffness. The customizable insoles are usually heat-molded to the arch by a technician in a weight-bearing or semi-weight-bearing position. It is common that the insole manufacturers educate and train retail ski staff according to their own philosophies often using self-serving and biased information that lacks scientific validation.

Considerations for Insoles and Custom Foot Orthotics

It is well established that humans do not respond in systematic ways to biomechanical interventions, so clinicians must rely on the best evidence, their clinical experience, and training to determine the optimal interventions for any given patient. This section does not discuss pathology-specific orthotic prescriptions but rather focuses on general insole and orthotic concepts in regard to XC skiing.

As with any footwear intervention, the biomechanics of the activity and the structural features of the footwear need to be considered when prescribing and manufacturing devices for the unique needs of the athlete. Medical professionals always have to be aware that the foot orthoses do not function in isolation—it is one component of the foot-shoe-ski interface. For high-level skiers it may be necessary to send the ski boot to the lab along with the cast in order to optimize the fit for custom foot orthoses. Because a flat ski glides more efficiently than a ski on edge, the goal of the orthoses should be to balance the skiers foot alignment in the frontal plane to maximize the time spent in a flat ski position. A hyperpronated (or planus) foot would be more likely to overload the medial edge of the ski as the rearfoot everts and the medial longitudinal arch collapses. Conversely, a supinated (or cavus) foot would tend to overload the lateral edge of the ski due to rearfoot inversion and medial longitudinal arch rigidity and/or a plantarflexed first ray. Forefoot-to-rearfoot malalignments must be balanced with the foot orthotic device in both conditions as well.

For both XC disciplines, efficient ski technique is dependent on optimal single-leg balance as the skier has to be able to maximize glide on each ski to conserve energy. Research has shown that postural sway increases with lower extremity muscle fatigue [33]. It has been speculated that molded insoles have the potential to delay the onset of fatigue and to improve proprioception which could then improve balance. A systematic review by Christovao and colleagues in 2013 found that insoles of various designs improved postural balance and control [34].

Poor skiing technique and/or poor balance have been implicated as issues that may contribute to excessive frontal plane motion resulting in less than optimal performance and potentially increasing the risk of falling and overuse injury. Mattacola and colleagues found that single-leg postural stability was improved in subjects with rearfoot malalignment (varus or valgus > 5°) when using custom foot orthoses [35]. In fatigued, uninjured subjects other researchers found that semirigid custom orthoses significantly reduced postural sway [36]. Although these studies were not done on XC skiers, balance is such an important part of good ski technique that they provide a potential reference point for use of orthoses to improve a component of balance and secondarily improve performance and decrease risk of injury in XC skiers.

In regard to injury, a study on the Swiss national ski team concluded that biomechanical interventions which included custom foot orthotics reduced pain and overuse injuries over a 3-year period [37].

Summary

The two disciplines of XC skiing use slightly different equipment and footwear which are unique to the respective technique demands of each. Ski boots must combine comfort and performance features based on the personal preference of the skier. There is adequate evidence in the research that insoles and orthotics can improve balance and delay fatigue which may result in improved performance and/or reduced injury risk. Further research is needed however.

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Basketball and Volleyball

28

James M. Losito

Basketball and volleyball are clearly similar sports with regard to their ballistic nature and the need for lateral (side-to-side) movement. The primary difference is that there is no consistent running in volleyball and basketball does not generally involve lunging or diving on a regular basis. Current design strategies in court shoes are aimed at lateral stability, torsional flexibility, cushioning, and traction control to decrease the risk of injury [1].

The shoes worn in basketball reflect the physical requirements of the sport: the shoe must allow for running, jumping, and lateral movement and while providing primarily lateral stability to the subtalar and ankle joints (Fig. 28.1). Good fore-foot cushioning is also desirable because the majority of the impact occurs on the fore-foot. Most basketball shoes are composed of a blown or gum rubber outer sole. As with some running shoes, the manufacturer may interpose gel, "air" or other materials placed in the midsole which are often visible on the outer sole. The goal is optimal traction and stability on a wooden or concrete surface. The midsole is generally composed of ethyl vinyl acetate or a polyurethane foam material. Some manufacturers will augment the midsole with pockets of gel, "air" or other systems designed to increase stability and shock absorption. The most recent of these midsoles is a mechanized system by Adidas which can be used to adjust the desired amount of stability or cushion. The battery is included. The fine balance between cushioning and stability is critical and the inverse relationship understood. McKay and associates found that players wearing shoes with cushioning air cells were at greater risk for a lateral ankle injury [2]. Another requirement of the outersole and midsole in a basketball shoe is that the minimum required material is utilized. This allows for the shoe to be kept as low to the ground as possible. The Wade line of shoes by Converse exemplifies the desire for the shoe to maintain a low profile.

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Fig. 28.1 (**a** and **b**) Basketball shoes must allow for running, jumping, and lateral movement, while providing lateral stability to the subtalar and ankle joints. (Courtesy of New Balance, Boston, MA)

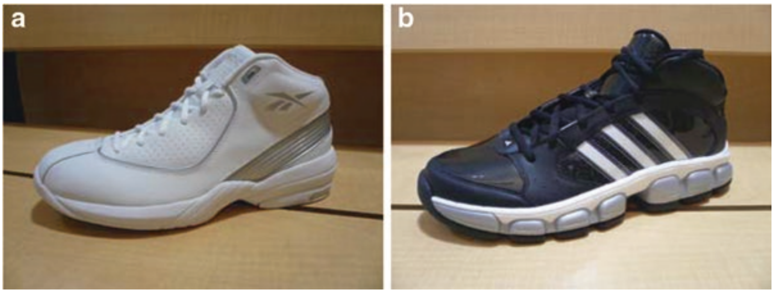

Fig. 28.2 (**a**) High-top Reebok basketball shoe. (**b**) High-top Adidas basketball shoe

The combination of outersole and midsole determines the properties of the shank. It is essential that a basketball shoe has solid shank stability. The shoe should never have sagittal plane flexibility in the shank region. Some manufactures have reinforced the shank with fiberglass, plastic, or graphite material in an attempt to reduce bulk but maintain stability. Failure to maintain shank stability may contribute to a variety of problems including plantar fasciitis.

Perhaps the most well-known feature of the basketball shoe is the high-top construction which has characterized the sport (Fig. 28.2a, b). Prior to 1980, the vast majority of basketball shoes were constructed above the malleoli in an effort to provide lateral stability and reduce the incidence of lateral ankle inversion injuries. However, more recently basketball shoes have been increasingly constructed at or below the malleoli (three-quarter or low-cut). The reason for this is probably fashion driven, but the lower cut construction does allow for increased mobility of the ankle and subtalar joints which is certainly beneficial. There is evidence that high-top construction may actually increase shock transmission and reduce both running and jumping performance [3]. Most importantly, research has shown that even the highest top basketball shoe does very little in preventing lateral ankle injuries [4, 5].

Fig. 28.3 Volleyball shoes are low-cut below the malleoli (Courtesy of New Balance, Boston, MA)

Volleyball shoes similarly are designed with the needs of the sport in mind. Gum rubber is the most commonly used outersole material. As with basketball shoes, the midsole is composed of ethyl vinyl acetate or polyurethane foam with occasional augmentation by gels and “air” cells. Volleyball shoes are all low-cut below the malleoli to allow for the frequent lunging and diving which occurs (Fig. 28.3). As with many basketball shoes, the desire to keep the shoe low to the ground for improved lateral stability is seen. As with basketball shoes, a stable shank is essential.

Custom Foot Orthoses

Custom foot orthoses usage in basketball and volleyball is common among recreational, collegiate, and professional athletes. Experience estimates that over 50% of basketball players and 30% of volleyball players utilize some type of pre-fabricated or custom foot orthotic device. These orthotic devices are prescribed by podiatric physicians, orthopedic surgeons, athletic trainers, physical therapists, prosthetists, and chiropractors. The variety of devices range from a leather insole with a heel lift and scaphoid pad to a custom functional orthotic device composed of thermoplastic and foam materials. The majority of orthotic devices utilized today are composed of light, resilient thermoplastic materials [6, 7].

In my experience, the most common orthosis requirements in basketball and volleyball are cushioning and stability. There is no true heel to toe progression for any significant amount of time during either of these sports and therefore the concept of the orthosis “functioning” is not possible. The orthosis usually fabricated is a hybrid with features of both a functional and an accommodative device, utilizing a semi-weightbearing casting method, often with foam. Maintain subtalar joint neutral position during casting and capture any forefoot deformity. Non-weightbearing neutral suspension casting technique may be utilized if desired; however, the laboratory should be instructed to use generous amounts of arch fill and lateral heel expansion because these athletes generally do not tolerate orthosis which are biomechanically correct. It is essential to balance any forefoot deformity as this prevents rearfoot compensation and increases subtalar and ankle stability. Malalignment such as forefoot valgus and rearfoot varus may predispose to lateral ankle injury [8]. It is best to apply any forefoot balancing extrinsically as only forefoot contact may occur during activity. In addition, orthoses have been shown to improve postural control which may also improve lateral ankle stability [9]. The typical device is composed of a polypropylene or polyurethane shell with some degree of arch fill composed of soft or medium-density ethyl vinyl acetate. Include a heel cup of at least 16 mm and any other modifications depending on the pathology being treated, and it is common to use a top cover of perforated ethyl vinyl acetate or microcellular rubber (Spenco). If additional cushioning is desired, add 1/16 in. Poron below the top cover. If shoe fitting is a problem, then arch fill can be reduced or eliminated. Forefoot thickness should be at least 1/8 in.

Sport-Specific Pathology

Lateral Ankle Sprain

As with most sports, the lateral ankle sprain is the most commonly encountered injury in basketball and volleyball. In fact, the lateral ankle sprain occurs more commonly in basketball than in any other sport [10]. The best preventive measure and management involves physical therapy and rehabilitative exercise, especially proprioceptive training [11, 12]. Ankle braces have been shown to improve ankle stability and reduce the incidence of inversion ankle sprains without adversely affecting athletic performance [4, 12]. Experience shows that basketball players favor lace-up braces and volleyball players generally prefer a more rigid device. As mentioned previously, custom orthotic devices have also shown some efficacy in the prevention and management of lateral ankle instability. The typical orthosis modifications include forefoot balancing, a lateral heel cup of 18 mm, and a lateral flare to the rearfoot post. In some cases a valgus forefoot post can be used to further stabilize the midfoot.

In cases of severe or chronic ankle sprains such as syndesmotic injuries, a Richie brace ankle foot orthosis is an excellent option for balancing the foot and obtaining maximal subtalar joint and ankle stability. Although this device is frequently used for tibialis posterior tendon dysfunction, it has excellent indications in cases of chronic ankle pain or instability.

Plantar Fasciitis

The second most common pathology encountered in both volleyball and basketball is plantar fasciitis. Both distal and proximal ("heel spur syndrome"). This ubiquitous overuse injury can be instigated by an unstable (flexible) shank and ankle equinus, which is considered to be the primary etiology [13]. With this being said, the most efficacious form of management is Achilles stretching, either manually or with a plantar fascial splint [14, 15]. Physical therapy, non-steroidal anti-inflammatory medications, injectable corticosteroids, orthotic devices, and extracorporeal shock wave therapy have all proven to be effective to some degree [16–18]. Regarding orthotic devices, there is evidence to suggest that pre-fabricated insoles compare favorably to custom orthotic devices [19]. However, in resistant cases, the use of a custom device, derived from a non-weightbearing neutral position cast with emphasis on plantarflexion of the first ray during casting is recommended. Balance the forefoot in slight valgus with a reverse Morton's extension to further promote first ray plantarflexion. This will reduce the tension on the plantar fascia [20]. Varus posting should be avoided as this will increase tension on the fascia [21].

Other Injuries

A variety of other injuries are frequently encountered in both basketball and volleyball. These include sesamoiditis, metatarsalgia, metatarsal phalangeal joint capsulitis, first metatarsal phalangeal joint sprains ("turf toe"), Achilles tendonitis, tibial fasciitis ("Shin splints"), Jones fractures, and digital nail problems. Tibial fasciitis or "shin splints" is the most common overuse leg pain encountered in basketball and volleyball [22, 23]. The etiology is generally overuse in combination with ankle equinus, anterior leg muscular weakness, and biomechanical flaws [22–24] Excessive subtalar joint pronation is a frequent contributor to this injury as well. Orthotic devices can control excessive subtalar or midtarsal joint motion and may be useful in the prevention and management of shin splints [22].

Jones Fracture

The Jones fracture is a type of stress fracture located at the metaphyseal–diaphyseal junction of the proximal fifth metatarsal. This injury seems to be more common in basketball than in volleyball. The Jones fracture has a poor prognosis for healing with conservative care, with the non-union rate as high as 50% in some studies [25, 26]. Therefore, surgical intervention is therefore the treatment of choice for many athletes. Following surgery and immobilization, a custom orthosis may be useful in the prevention of recurrence, using a custom orthotic device with a modification designed by William Olson, DPM (2000, personal communication). The Jones fracture modification involves expanding the lateral aspect of the positive cast to produce an accommodation for the fifth metatarsal in the orthosis shell. A high lateral flange is then created which is directed over the metatarsal and the device is flat-posted (0° of motion). As with most custom sports orthoses, polypropylene is the material of choice. As previously noted, the shoe must provide a stable shank and lateral (side-to-side) stability.

Summary

Clearly, there exist many available orthosis modifications in the prevention or management of basketball and volleyball injuries. An orthotic device with a metatarsal bar or raise along with forefoot accommodation is useful incases of metatarsalgia or metatarsal phalangeal joint capsulitis. A reverse Morton's extension with accommodation plantar to the first metatarsal phalangeal joint may be useful in the management of sesamoiditis. A thin, rigid extension plantar to the first metatarsal phalangeal joint may be useful in cases of structural hallux limitus, but may increase the likelihood of gastrocnemius strain or shin splints.

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Aerobic Dance and Cheerleading

29

Jeffrey A. Ross

Aerobic Dance

For over 30 years, aerobic dance has been one of the most popular forms of cardiovascular exercise in America. Step/bench aerobics has evolved from a high-impact aerobic "exercise dance" form with a high degree of lower extremity injuries to a safer form of low-impact dance. The reduction of impact shock to the lower extremities has aided in the reduction of the number of lower leg and foot injuries seen by the sports medicine specialist. Initially, aerobic dancers would participate in their workouts on a floor consisting of a thin carpet and padding overlying an unrelenting concrete floor. Both exercise physiologists and sports medicine specialists saw the need for change in the surface and promoted the high-tech air-suspended wooden floor surfaces. The reduction in these injuries has been multi-factorial. For instance, the aerobic dance instructors and the participants are better trained and much more informed than they were years ago. Cross-training and new facets to the exercise routine with the addition of "kickboxing" and "urban rebounding" have helped to break up the routine and help to reduce injuries. Health magazines, instructor certification, improved aerobic and cross-training shoe design, better supervised instructors, and a better educated medical community have all led to the improvement and prevention of injuries [1].

Approximately 20 years ago aerobic dance evolved into a new form utilizing a "bench" platform and created an aerobic exercise equal if not better in its cardiovascular benefits, while reducing the impact forces to the lower extremity. The exercise routine is performed on a "step" that is 43 in. long by 16 in. wide by a minimum of 4 in. high (109 cm × 40 cm × 10 cm). At the onset it was thought that the higher the bench, a harder and more vigorous workout could be accomplished. However, over

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Table 29.1 Terminology for aerobic dance

Helicopter move (half-hop turn)
Inner thigh
Diagonal lunge
Power knees
Leg extensions
Over the top
Straddle the bench
Double-knee with jog
Jack and jump
Karate and squat

Fig. 29.1 Nike Musique IV women's dance shoe

the years, and with research on the sport, it was determined that with elevations of one, two, and three block increments, the risk of overuse injury increased [2].

In addition to the new equipment used in the dance studio, a new vocabulary aimed at directing the participants to specific dance steps had to be developed (Table 29.1). For the beginner aerobicizer, learning this new language was imperative, otherwise participating in the early stages of the routine could become very frustrating [1].

The foundation to any sport is the shoes the participant wears. As in running or other sports technological advances in design have led to a much more stable, high-performance shoe (Fig. 29.1). Additional changes in design have led to the newer breed of shoe known as the *cross-trainers*. These shoes permit the participant to perform aerobic dance while engaged in minimal short-distance jogging. With increased running incorporated into the routines, combined with lateral and back-peddling dance movements, the cross-trainer is a vital part of the aerobicizer's standard foot wear.

One of the most important factors in injury prevention in step/bench aerobics is the keen observation of the instructor. Most aerobic instructors agree that technique is very important in the avoidance of dance injuries and that repetition is dangerous.

A study conducted of aerobic dancers has shown that an aerobic dance routine performed at a cadence that was extremely fast (over 128 beats per minute) did not allow for the participant to secure his/her entire foot on the bench. This can cause the foot to hang over the edge of the bench, causing strain or an enthesis of the Achilles tendon, as well as the posterior tibial tendon or the peroneal tendons. This can also lead to a strain of the medial or central bands of the plantar fascia, or the intrinsic musculature of the plantar aspect of the foot [1, 2]. Additionally, an over the top step off the bench can lead to a number of overuse impact injuries. These can include stress fractures of the lesser metatarsals, navicular as well as the tibia or fibula, sesamoiditis, tarsal tunnel syndrome, or the interdigital neuroma formation. Biomechanical considerations, and the use of prefabricated insoles or custom foot orthoses, may be needed for these foot conditions. If the participant extends the foot too far backward off the bench, hyperextension of the ankle with concomitant traction of the Achilles tendon can occur. If left undetected, and with repetitive loading, a chronic Achilles tenosynovitis, paratendinitis, or insertional calcinosis can develop. Knee alignment is also crucial in relation to the lower leg, as well as the placement of the foot on the bench. It has also been reported that striking the floor from the bench with repetitive impact can cause chondromalacia patella, patellofemoral joint syndrome, or chronic posterior shin splints [2]. It is imperative that the aerobics instructor surveys the participants before initiating activity to determine if any have pre-existing overuse injuries, or if there is a high risk for developing an injury. A pre-dance evaluation by the sports medicine foot specialist can determine—using visual or computerized gait analysis—if the participant is at risk for developing an overuse injury. Recommendations on flexibility stretching, proper shoe gear selection, and improved range of motion to foot, ankle, and knee can be made.

Older instructors who have been teaching for over 10 years, and have taken the proper certifying courses, seem to teach safer classes and know how to prevent the pitfalls of overuse injury. On the other hand, inexperienced younger instructors who have not yet developed those supervisory skills may be more likely to induce injury to participants.

There are a number of factors that can help lower the incidence of these overuse injuries: certifying instructors, carefully selected music (pacer per minute), smooth choreography, cueing to the beat of the music, as well as the participants taking the class. The predicament for the instructor is to choose between a safe and an efficient workout, while providing for an aggressive and challenging one that could lead to an overuse injury [2].

Prevention of injuries for the aerobic dancer athlete should be a concern for the sports medicine specialist. These aerobicizers train at high levels and often ignore the potential for injury. Many may actually dance through an injury similar to runners who run through an injury in order to continue to participate and avoid downtime. Many of these participants may have physical or psychological disorders (i.e., amenorrhea, anorexia nervosa, osteoporosis—the "female triad") which can have serious repercussions when they first begin an aerobics class. The sports medicine specialist should be on the alert when interviewing the patient during the history taking, since any one of these diagnoses can render clues as to the underlying injury. Extreme weight loss, and/or stress fractures (particularly in the young female athlete), should raise suspicion for the sports medicine practitioner to look beyond the easily definable diagnosis and consider referral to the appropriate specialist [1, 3].

In a preliminary investigation by Ross of 329 participants surveyed, 153 claimed that they had suffered some discomfort or pain due to step/bench aerobics, whereas 163 claimed that they were symptom-free [1, 2]. Of those injured, 43 claimed that they had sought treatment by a foot specialist. Shoes seem to be another consideration, with 105 responding that they had some problem with their shoes (i.e., blisters, improper fit, not enough support, cutting off circulation, irritation), while 197 denied any problems with their shoes. The most common sites for the incidence of injury were the (1) knee, (2) calf, (3) Achilles tendon, (4) foot, and (5) shin.

Instructors interviewed during the study made the following recommendations:

1. Keep the knees slightly bent, never locking the knee.
2. Bring the foot all the way up to the bench, so that the heel is not hanging off.
3. Keep the knee over the ankle (creates less strain on the knee).
4. Push off with the heel (not with the knee) with either squats or lunges.
5. Keep the head up and the chest tall (to prevent lower back strain).
6. Avoid stepping too far away from the bench.
7. Avoid stepping overenthusiastically or ballistically off the step.
8. Maintain the same pace and avoid stepping too quickly.
9. Do not be afraid to lower the bench to a level more suitable to your abilities to avoid injury.

It was important to note that the instructors felt (1) the class size was important in order to observe properly, (2) keeping the pace of the step at 128 beats per minute, whereas exceeding the pace would not allow the entire foot to rest on the bench, (3) technique was extremely important to avoid injury, (4) excessive repetition of the steps can lead to injury, (5) keeping the height of the benches under three platforms: hyperextension of the knee can occur with more, and (6) stretching and warm-up prior to activity is essential to avoid injuries.

Step and bench aerobics have become a very popular form of exercise work-out for the enthusiast. Careful monitoring of the participants has been shown to be helpful in avoiding injuries. For the sports medicine practitioner, understanding the mechanics of the sport, the terminology, as well as the biomechanics of the individual participant can help predict what injuries may occur and how to properly diagnose and treat when the occasion arises.

Urban Rebounding

Other forms of aerobic dance have surfaced over those few years, with one exciting form of aerobic workout entitled *urban rebounding*. The urban rebounding system was created by J. B. Berns, a practicing martial artist. The workout has its roots in the martial arts and core body postures, resulting in a non-stop abdominal workout, which strengthens the core and improves balance and coordination. The workout begins with the use of a small trampoline referred to as the urban rebounder.

The warm-up consists of a series of jumps and toe taps. The exercise consists of about 30 min of a combination which progressively adds moves to include “straddle hops,” “knee-ups,” and jumping jacks. The next part of the workout includes interval training in which a series of jogs is followed by sprints, picking the knees up as high as possible. The spring in the rebounder allows for recoil without the impact of a floor aerobics program or jogging. Certain movements are able to be performed on the rebounder such as a basic bounce, straddle, lateral knee raise, jumping jacks, twists/double twists, 180° turns, military press, forward jump, upright row, and forward knee abdominal crunch. There are also sports-specific moves including the four jog sprints, vertical jumps, 180° spins, and power jump/knee tucks [4].

Biomechanical considerations for this whole workout is as important as with step/bench aerobics. Foot position on the rebounder is essential. Proprioception of the foot and ankle on the rebounder is also critical. A rebounder participant should not participate if previous ankle injury or ankle instability is present. Since there are so many deep knee lunges (similar to alpine skiing—great preparation), a participant with chondromalacia patella should avoid this workout as well. Quadriceps strengthening for this workout would also be recommended. Shoe consideration is also important, with worn out or distorted shoe counters a reason for elimination. Balanced, stable motion control shoes are essential for this workout program. Biomechanical balancing with orthoses may also be necessary. This core body and lower extremity workout has many advantages over the high-impact or bench-type aerobics program; however, lower extremity considerations are very apparent and need to be focused prior to initiating this workout.

Kickboxing

This aerobic exercise routine combines martial arts and aerobics together. With upper body arm movement and leg extensions and kicks, this intense workout can help to build upper body as well as lower body strength. Proper lower extremity flexibility is essential before knee flexion and extensions are attempted. Balancing on 1 ft and attempting to extend the opposite foot can place increased strain upon the support limb. Rotation of the hip and extending the lower limb again places stress upon the support limb. Kickboxing has been shown to be an excellent form of aerobic training which increases cardiovascular endurance. Foot balance and lower extremity strength is essential in order to perform the movements properly. As in step/bench proper instructor supervision of the participants’ movement can help to avoid overuse injury.

Cheerleading

Cheerleading's roots can be traced back to a cold day in the 1880s on the Princeton campus when the "locomotive cheer" first came upon the scene. In 1884, Thomas Peebler, a graduate of Princeton University, took the locomotive cheer and shared with his students at the University of Minnesota the first cheer. On a crisp fall day, November 2, 1898, on the Minnesota campus, Johnny Campbell began the first official cheerleader "yell." The father of modern cheerleading was Lawrence "Herkie" Herkimer from Southern Methodist University, who eventually formed the National Cheerleading Association.

In cheerleading various movements are important. Jumps, stunts, basket tosses, and tricks, and lunges are just to name a few. Beginning with the motions and cheers that cheerleaders engage, leg positions are a vital part of the cheer. Three leg positions are involved, namely the lunge, back lunge, and the wide. The lunge is performed by keeping the front leg bent and the back leg straight. The straight leg classifies the lunge as either "right" or left. The back lunge is accomplished with the front leg bent. The hips should face forward and the other leg should extend back. Weight is on the back leg. The wide position is created by keeping the leg stance open, slightly wider than the shoulder width apart [5].

The second important category is jumps. The most popular jump is the toe touch, followed by other jumps such as the front or side hurdler, double nines, and around the world. In the toe touch the position creates the appearance of a hyper-extended jump. It requires a strong hip flexor together with a powerful jump off the ground. In the front hurdler the cheerleader snaps his/her front leg up to the chest, keeping the back leg bent behind the body. On the jump, the arms are extended directly in front of the athlete. The side hurdler is accomplished in the same fashion but with the torso facing the side direction, rather the forward. The around the world jump is performed by creating a front pike that opens up into a toe touch. The double nine is not as common and is performed by making the shape of the figure nine. There are a number of jump drills that the cheerleader can perform in order to perfect their jumps. The straight jumps, the tuck jump, frog jump, snap-ups, standing one-leg snap-ups, seated leg raises, and repetitive jumps are just a few. These jump drills are a part of the practice and help to improve jumping skills.

Stunting is probably the most colorful part of the cheerleading experience and can be one of the most dangerous in terms of injury (Fig. 29.2). Each cheerleader has a specific role and position in stunting and should rotate in their participation just to understand what their teammates' roles are like. The various roles are the following: the flyer, who will be tossed and flies through the air; the base (or bases) who perform the toss, holds, and supports the weight of the flier; the third, responsible for the back portion of the stunt and assists the bases with tossing, holding, and supporting the flier. The third is regarded as another base member. The spot (or fourth) is there to "spot" and ensures the safety of the stunt and to assist with the stunt as necessary [5].

Spotting drills are very important and help to ensure the success and safety of the stunt. They also help to build trust with each member of the "team."

Fig. 29.2 Each cheerleader has a specific role and position in stunting (Courtesy of All-Girl Cheerleading Club on NC State University, Raleigh, NC)

The various drills used are the step off where the athlete practices both stepping off (flyer) and catching (base) roles. The platform will gradually be raised to increase the level of difficulty. The lower down is the next progression from the step off drill. The athletes load the flyer up into a stunt and then slowly lower her to the ground level. The fall-back cradle is where the athlete familiarizes themselves with being caught in a cradle. The cheerleaders should familiarize themselves with holding the flyer in the cradle catch before attempting to catch a flyer from a backward fall [5]. These drills are intended to help prevent injury to the flyer. Each member of the team has a specific role and is vital to the success of the stunt and to the safety of the flyer. The dismount of the flyer is the way in which they are brought back to the ground. The most common dismounts are the “pop down” and the “cradle.” Multiple bases and multiple pyramids are developed to enhance the various stunts and to optimize the trajectory of the flyer. Many of these designs can be quite complex and take a significant amount of coordination, particularly with the toss and catch of the flyer.

Pre-conditioning, flexibility, strengthening, and coordination are essential for success in the cheerleader’s routines. Injury prevention is essential; however, injuries do occur. Ankle strains are probably one of the most common injuries encountered in this sport: stress fractures of the foot, knee injuries, and overuse muscular injuries, just to name a few. The sports medicine specialist is an important part of the cheerleader program and should regard these athletes as important as the football or basketball players whom they cheer for. When injuries do occur to the cheerleader, “downtime” can be just as devastating as to the athlete on the field or court. Psychological as well as physical support is just as important.

Cheerleading has become a very popular sport with serious competitions between teams as seen on the nationally televised scene. Cheerleading clubs in addition to scholastic cheerleading squads have become just as popular for the young athlete. Dance routines, acrobatics, and gymnastic skills have become integrated in the cheerleading routines, which have added to their complexity. Again, the sports medicine specialist should be familiar with many of the terms, and movements of the sport, to understand how injuries may occur.

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Dance and Ballet

30

Lisa M. Schoene

Athletic Footwear and Orthoses in Sports Medicine: "The Dancer"

Lower Extremity Biomechanics and Considerations in the Evaluation of the Dancer

Today, the dancer's body appears in many shapes and sizes, due to an increasing interest in dance forms other than ballet, i.e.; tap, modern, jazz, hip hop, and Irish dance. For many years dance has only been seen as an "art form," now we must realize the rigors and athleticism that is necessary to perform. The differing styles of dance all place high demands on the body, which parallels or supersedes that of any other demanding sport. "Only the astronaut in our society is a more selected individual than the professional ballet dancer" Dr. William Hamilton [1].

The traditional starting point for a dancer is the five universal ballet positions, which are taught early during ballet classes. These positions are carried throughout the dancer's career, as ballet is the staple to which most forms of dance training emanates from. There are some variances within each of the dance forms, so the stresses on the lower extremities will be a bit different. Classic ballet dancers dancing en pointe will have different stresses on the lower extremity and body, than a modern dancer who may be lifting another female dancer or performing on the floor using acrobatic movements barefoot. Understanding the universal but different nuances within each style of dance can help the evaluation and treatment process. Dancers have lower extremity injury rates well over 50% and it is noted that dancers have been shown to sustain more lower extremity injuries than that of collegiate athletes [2, 3].

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Many factors come into play when determining why an injury occurs. These factors include intrinsic and extrinsic means. Common intrinsic factors that may contribute to injury in the dancer are; sex, age, body weight, height, menses onset, sleep hours, nutritional factors, psychological/personality traits, skill level, foot biomechanics, flexibility, strength, balance and coordination. The extrinsic factors that may cause injury include; flooring issues, choreography changes, increased rehearsal time, class schedule changes, dance shoe issues, rehearsal room temperature, set design, lighting, and music tempo. Both intrinsic and extrinsic factors have been determined to be in part, the cause of overuse and traumatic injury in dancers.

Although there are some challenges within the literature determining how to define the causes for injury and exactly what, and when injury occurs, this author believes the combination of many of the above factors are the cause, and can vary tremendously for a particular dancer within a year's time. For instance; a dancer may come from a school or studio program in May, head into an intensive training over the summer for 6 weeks, then have time off, but followed by a new job and rehearsing for a show with a new style of choreography in the winter etc. For that reason, all these factors must be included in the injury assessment and history taking. For those serious dance medicine practitioners, a dancer questionnaire history form will be helpful in this process. It should include questions on menses, diet, current and previous injuries, class schedules, types of dance classes attended, sleep hours, cardio activity, and smoking to name a few.

During the physical exam the whole kinetic chain including a thorough biomechanical foot exam should be performed. Injuries may be located at areas of compensation, but the deformity or dysfunction may be located elsewhere along the chain, especially within the foot. During the evaluation, include static and dynamic flexibility and strength tests. Standing, and gait exams, as well as having the dancer demonstrate functional dance based movements, are important to screen for. Having a basic knowledge of dance positions and basic techniques are strongly suggested in order to make the evaluation process more efficient. The dancer should have on shorts and t-shirt or a leotard in order to accurately see alignment of the foot, the lower extremity, and spine.

Posture and Technique

The body is in optimal position, when the joints align properly, therefore postural exam is important. Adjustments can be made with teaching simple que's, strengthening, habit awareness, and re-education. Thinking of a plumb line, the head should be centered with the ear over the shoulder, to the center of the hip, following a line slightly anterior down the tibial shaft down to the ankle through the malleoli (Fig. 30.1). Technique, is perfected with regular and consistent instruction and training, and when it is faulty, it can instigate many injuries.

Proper technique starts in the early years, and should improve with age, proper guidance, and gentle advancement towards improved flexibility, and strength. When the dancer approaches the time to go up en pointe, shoe fitting, and proper technical

Fig. 30.1 Courtesy of "Russian Pointe"

preparation is even more important and precise. The dancer needs to be prepared both physically and emotionally, as this portion of ballet training is the most challenging. Due to the incredible nature of pointe work, it is understandable that many dancers struggle with injury. The injury patterns do differ in the young pointe dancer vs. the more elite or professional pointe dancer. Time, experience, and consistent study are important for progress. It is at this time, foot and ankle strengthening exercises will be very helpful.

General Flexibility, Strength and Balance

The question is always do these athletes choose dance or does dance choose them? Many believe, it is a self-selection process, as inherent ligament laxity is a typical trait of the adolescent and professional dancer, (as well as for gymnasts, and skaters), where extreme flexibility and joint position demands are high. These extreme ranges are not typically required by most other sports. Age appropriate and safe flexibility and strength exercises should be included in early dance training by the dance teacher or other dance medicine specialist. Most dancers choose to do static stretching during warm up, and although it may reduce some muscle damage, it has been studied that dynamic stretching is best and does not cause strength loss like persistent static stretch holds [4].

Fig. 30.2 Plantarflexion of foot

Fig. 30.3 Dorsiflexion of foot

Fig. 30.4 Eversion of foot

Fig. 30.5 Inversion of foot

Fig. 30.6 Plantarflexion of hallux using the FHL

Fig. 30.7 Plantarflexion of the lesser toes using the FDL

Strengthening, the foot intrinsics and extrinsic muscles can be done by using traditional rubber tubing. The dancer can easily store a piece in the dance bag (Figs. 30.2, 30.3, 30.4, 30.5, 30.6, 30.7, 30.8 and 30.9). Cross training work with Pilates, weight training, or yoga can also help all dancers improve dynamic movement patterns. Pointe work requires incredible strength, balance, and technique along with proper

Fig. 30.8 Plantarflexion of the First Ray strengthening the Peroneus Longus

Fig. 30.9 Strengthening the Intrinsics using the towel method

Fig. 30.10 Is testing strength in turned out 2nd position

alignment of the foot, knee, and hip. Abdominal and hip strength can be tested statically on the table in parallel and turned out positions including second position (Fig. 30.10) also by front and side planks, double leg lowering test, and some dance jumps. General balance and coordination will present itself within these other tests, but may differ among dancers of different ages, especially in pre and early teen years, as these abilities may regress a bit while the dancer moves through growth spurts. Discussion with teachers and parents will help to soothe worry away, as things will return to normal in time.

Foot and Ankle Requirements for Dance

Due to the nature of the various forms of dance, the foot and how it functions is an extremely valuable asset. From the classic ballet dancer, the hip hop dancer to the theatrical dancer, foot alignment, functional aesthetics, and how it works, will get the dancer far as it relates to injury and possibly job security. The best shape for the ballet dancer's foot is having all the toes or at least the first three toes the same length. Reports of varying toe lengths may predispose this dancer to stress fractures and other soft tissue injury [5]. A nicely formed longitudinal arch is ideal, however some unnatural and extreme arched feet have emerged as the "new norm." Dangerous practices of extreme foot stretching exists as many young ballet dancers will strive to get that aesthetic, as they work the arch by stretching it and potentially injuring the precious ligaments in the midfoot, all to produce the extreme degree of that "arched" attitude needed for the pointed position.

Stressing the importance of safe and progressive stretching is paramount, and rather best to teach the dancer on proper plumb line alignment, and proper strengthening of the foot muscles that actually plantarflex the foot, to give it a strong and beautiful arched position. In regards to weight bearing stresses, during a technique class, a dancer will endure up to 200 jumps, and may put upwards of four times body weight on each foot per jump with only a ballet slipper on. While en pointe the dancer will sustain upwards of 12 times body weight while jumping [6, 7]. Laboratory studies have shown, that a 115 lb. dancer who sickles only 2° rather than being perfectly on the flat part of the box of the pointe shoe (or perpendicular to the floor), will transfer an additional 40 lbs. to the lateral ankle, which is most vulnerable to sprains [8]. This technique problem has profound effects on alignment and potential injury. Add some of the above listed intrinsic or extrinsic factors and it is easily realized why there are so many injuries in dance. For the ankle joint, normal adult plantarflexion is approximately 50°, but for a dancer approximately 90° is needed for proper pointing positions and dance movements.

A quick check for alignment and plantarflexion of the ankle can be done using a pencil test laying the pencil on the talus, when the foot is fully pointed, the pencil should line up parallel with the tibia [9] (Fig. 30.11). The midtarsal joint is also called the "coup de pied". This joint rotates plantarly as the talus plantarflexes. Proper movement at this joint is attained by the help of the five secondary plantarflexors: Peroneus longus, Peroneus brevis, Tibialis posterior, Flexor digitorum longus, and Flexor

Fig. 30.11 Pencil test for proper foot/ankle/tibial alignment

Fig. 30.12 Extreme high arched foot of a dancer not functionally well aligned

Fig. 30.13 Extreme high arched foot of a dancer, not functionally well aligned

Hallucis Longus. These muscles all insert distal to the talus thus allowing a proper lever arm for the forefoot to have a strong plantarflexory moment, to allow for an esthetically strong pointed foot. Ligament laxity from extreme stretching through the midfoot, or having weak secondary plantarflexors will all promote an undesirable (over arched) pointed foot position. This foot may look at first glance to be very arched with extreme pointed alignment, however functionally it will not stand the test of time and will potentially break down, causing injury (Figs. 30.12 and 30.13).

Also when these secondary plantarflexors, are not strong, the two primary plantarflexors; Gastrocnemicus and Soleus, will cause the calcaneus to be continually pulled into equinus, allowing the talus to slide down and forward creating a “locked” like affect, thus not allowing the midtarsal joint to rotate plantarly. Many dancers with these weaknesses, will complain that they feel like their foot is not attaining the pointed position they desire, or they may complain that they feel like the foot and ankle is “jammed”. Proper strength of those 5 “other” muscles is imperative to correct this problem, as it is often overlooked in the exam, or by dancers in general.

The Dancers Foot Exam

Evaluate the non and weight bearing foot. Assess the range of motion of the Metatarsal phalangeal joints, midtarsal, subtalar and ankle joints, and compare each side. Check the strength of the intrinsic muscles, and the extrinsic muscles. Testing both concentric and eccentric strength is important. The weight bearing exam should include measurements of resting and neutral calcaneal stance position (Fig. 30.14), forefoot position as it relates to the rearfoot, assessment of arch height, and a “releve” (rising up onto the toes) to check for good alignment, balance and proper toe alignment while balancing (Fig. 30.15). Evaluation of how the first ray and first metatarsalphalangeal joint (MPJ) function is key, is very important to help assess the ability of the dancer to be able to properly rise up onto releve in demi-pointe (half pointe), or up onto full pointe in the pointe shoe. In biomechanical terms pronated and supinated is equal to “rolling in” or “sickled” in dance terms.

Fig. 30.14 Resting calcaneal stance position

Fig. 30.15 Releve' position looking for proper balance

Normal range of motion (ROM) for the first MPJ in adults is 65°, but for the dancer, 90° is necessary for proper demi-pointe stance. In addition to the true non-loaded ROM of the first MPJ, the examiner can assess the dorsal and plantar excursion of the first metatarsal or first ray, as it relates to the second ray and check to see how the hallux dorsiflexes with loading. The peroneus longus is an important muscle for the proper function of the first ray, as it is continually activated when up onto demi-pointe as it is the primary plantarflexor of the first ray, it basically keeps the first metatarsal head firm against the ground. The peroneus longus EMG studies always peak at the time of jumping and toe-off [10]. In the pronated foot this muscle will lose that effective plantarflexory pull, hence the first metatarsal will elevate and cause dysfunction of that joint and first ray. This is not a good thing for a dancer needing the full 90° of dorsiflexion, so treatments aimed to preserve this important ROM is critical. This is demonstrated by the Hubschers maneuver; when the foot assumes that standing pronated position, the hallux cannot be lifted into dorsiflexion, but after aligning the midtarsal and subtalar joints correctly, the hallux can be lifted off the floor. This test can also assess the flexibility of the arch, but it perfectly demonstrates how the first ray is totally affected and improved when the alignment of the arch architecture is corrected (Fig. 30.16a, b) To test for the strength of the first ray, have the dancer plantarflex and evert the first MPJ against the examiners thumb (Fig. 30.17).

Evaluation of the dancer demonstrating all five dance positions on releve and demi-plie in each position, simple jumping techniques can be used for the evaluation process as well. While on the floor, the foot should have a three point balancing system, the first and fifth metatarsal and the heel. This triangle forms a base so the foot can work in a strong and supported system (11 was 5). As the dancer rises onto demi-pointe, plies or jumps the alignment should remain consistent through the ankle, subtalar, midtarsal, MPJ joints, and the knee should align nicely over the second metatarsal (Fig. 30.18).

Weight bearing foot X-ray evaluation is always helpful to assess the biomechanics of the foot as early recognition of foot deformities i.e., bunions and hammertoes can be seen. Early intervention to halt the progression of these deformities can be accomplished with functional orthotic devices and street shoe changes, to stop the abnormal

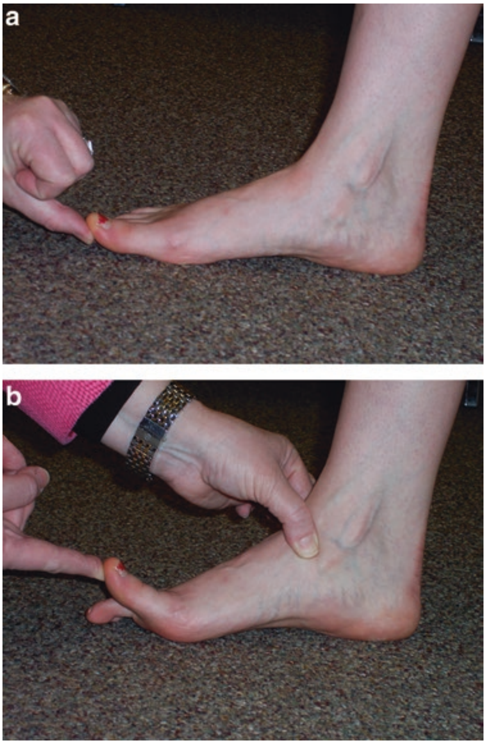


Fig. 30.16 (**a**, **b**) Hubschers maneuver to test for first ray function

Fig. 30.17 Testing the strength of the peroneus longus muscle

pronatory, forces and to reduce foot fatigue as well. Growth plates should be assessed in the adolescent dancer, as the common parental question, is if their child can start pointe classes prior to the closure of growth plates. Dancers typically start Pointe work between the ages of 9–13, with 11 or 12 being the average age, but will vary based on, length of training, weight, technical skill of the dancer, psychological

Fig. 30.18 Plie' with proper alignment of foot, knee and hip

Fig. 30.19 X-ray evaluation while in the pointe shoe

maturity and even the dance studio policy. The answer has to encompass all of the above factors, plus the assessment of the lower extremity examination by the dance medicine practitioner. The typical ballet dancer will be petite and if she is not menstruating the growth plates will not be closed prior to this new segment of her dance training. Assuring the parents that if done properly and slowly, pointe work will not retard any growth plate closure. X-rays taken with the pointe shoe on, placing the foot on pointe or demi-pointe can be helpful to see if abnormal toe or metatarsal positions are present within the shoe. This can be helpful when persistent toe pain, or painful lesions are present (Fig. 30.19). One common incidental X-ray finding, is increased cortical bone along the central metatarsals in experienced dancers due to increased loading on those rays of the foot, this is common and generally of no concern.

Foot Hygiene for Dancers

Although dermatology issues are rather mundane for the dancer, care and attention is vital, as blisters or open lesions can cause some off loading compensations. In a sport that is measured in millimeters, that matters! Proper callus, blister, and toenail care is very important and can prevent possible soft tissue infections if initiated early. Keeping skin and nails clean, and free from cracking and blisters helps to prevent infection, and pain while dancing. Gently pumicing and nail clipping are important for regular maintenance, and when an open sore exists, proper care should be instituted. When problems exist, simple digital padding, gel sleeves or blister band aids are helpful and do not take much room in the shoes, and can be worn for rehearsal or performance. Barefoot dancers may sustain floor burns, or splinters and may contract potential skin infections if the skin is repeatedly cracked or callused. It is important to keep ballet, and jazz shoes dry in order to extend the life and prevent trapped moisture. Mesh bags will help with this, as well as the use of powders and shoe trees for the more structured shoes to help keep their shape.

The Dancers Knee Exam

The knee should be evaluated non-weight bearing and weight bearing. Traditional knee exam should be performed. The alignment of the patellofemoral joint is very important, so evaluating the patellar alignment helps to assess for increased risk of patellofemoral syndrome, patellar tendonitis and/or patellar dislocation. Normal Q angle is under 15°, and since the typical dancer is relatively slender, abnormal angles are usually not present, however, when the gluteus medius, adductors and other core musculature is weak, and/or if the foot is abnormally "rolling in" while dancing (especially in the turned out positions), the knee will typically fall into valgus when performing plie's, jumps, or other movements. All these imbalances can aggravate the abnormal tracking of the patella, causing patellofemoral issues, medial knee strain, or patellar tendon issues [11].

It is not uncommon, and rather a desired esthetic for dancers to have slight genu recurvatum and/or genu varum as well. When treating the dancer with a knee injury, it is important to address the abnormal foot biomechanics and proximal weaknesses creating these alignment issues as soon as possible. Although common in adolescent girls in other sports, ACL injuries are less common in the dancer, most likely due to regular jump training, overall better hip and core strength, and proprioception control. Simple hip and core exercises can be administered and physical therapy modalities as well as kinesiology tapes, and arch padding etc. can be utilized under tights and in some shoes while dancing. Generally dancers can work through the more common knee pains while they continue to dance.

The Dancers Hip Exam

Proper ROM of the hip is critical for the dancer to attain the correct alignment for esthetic purposes and to safely perform the necessary movements. Normal adult external rotation is approximately 45–50°. Ninety degrees of external rotation is desired in the classical ballet dancer. As young dancers are working on the turnout "en dehors," teachers should allow it to develop safely and under supervision as it can take many years of training.

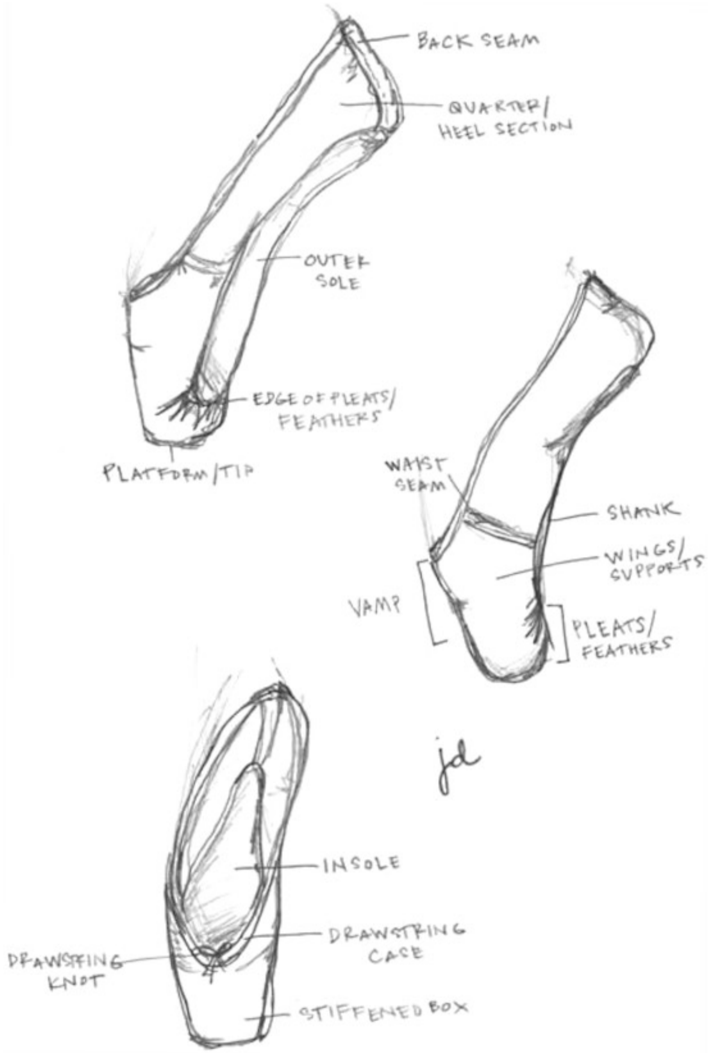
If the dancer does not attain at least 60–70° of turnout before advancing onto pointe work, it may be advised to hold on this advanced work. The individual's anatomy will ultimately be the determining factors, as the angle of the femoral neck, the orientation of the hip socket, and the tautness of the iliofemoral ligament may limit the abilities for excessive turnout. Early and steady training may have influence on the developing neck of the femur as well as the soft tissues surrounding the hip, but typically by the age of 11 or 12 further change is limited, but it is thought that continued soft tissue stretching may continue to help turnout a bit [11]. Functional turnout can be assessed, by using rotation discs or while looking at the first- fifth dance positions, checking for foot, knee, and hip alignment.

Evaluating the hip functionally with these dance maneuvers and jumps can alert the evaluator to hip weakness. The inability of attaining the full 90° hip turnout may prompt the dancer to cheat and push the turnout from the foot, knee, or by increasing the lumbar lordosis hence allowing the hip to appear as if there is more turnout than there actually is. All these compensations will most likely lead to soft tissue stresses and possible injury along the chain. Although the majority of the turned out position come from the hip, some acceptable minimal turnout is achieved via the knee, and foot as well. Excessive turnout from the foot or knee, can cause strain along the lower extremity chain, and should not be relied on for a large part of the desired external rotation. It is also noted and recommended by most dance medicine specialists, to encourage the dancer to not continually walk in a turned out position, but rather walk in a more parallel gait pattern, as it will take those continual stresses off the hip joints.

Footwear Recommendations and Modifications for the Dancer

Footwear is more structured in the tap, hip-hop or theatre dancer, less structured in ballet, Irish and jazz dancer, and non-existent in the modern dancer. Even when shoe use is limited it is still important that proper fit be considered. The ballet slipper or jazz shoe comes in canvas, or leather. As the shoe stretches, the fit will change. The toe area should be snug but not too tight as pressures on the metatarsal joints, soft tissue and/or nerves may be compromised. When toe or toenail pain exists, changing sizes may reduce the pain. The Pointe shoe comes in a satin material over layered paper or fabric, which is dipped with glue. These shoes break down between 10–20 h of usage, and are expensive, thus the fit and usage should be perfect.

The fitting process can be challenging even for the professional dancer, as many of the shoemakers/companies may be based overseas. Depending on dancer skill level and desires, the shoe can be made with varying shank stability, vamp shape, wing stiffness, and platform shapes (Drawing Pointe Shoe #19).



Pointe shoe construction. (Courtesy of the author)

The shanks will change in the pointe as she becomes stronger, and therefore she may need to change into different shoes. Even with the pointe shoe toebox, it is the dancer's foot that makes the pointed position, and her skill and strength allow her to rise up onto full pointe. Some dance schools suggest a de-shanked pointe shoe for the dancers preparing to go up onto pointe, as it makes the dancer work harder to point the foot, and adds some weight at the toe area, to prepare the dancer for regular pointe work [12]. The typical age for going up onto pointe is approximately 11 or 12. Pointe shoe fitting is critical and should be done by a professional fitter to insure proper esthetics and foot fit and function and to prevent the rubbing of toes that may predispose the dancer to corns and blisters.

Lambs wool is the preferred protection for the toes inside the toebox as silicone or rubber padding changes the fit, does not allow proper movement of the toes, and may make the foot perspire. Very thin padding (poron or plastizote) can be added inside the regular ballet slipper, jazz shoe, Irish dance slipper or even the pointe shoe to help with metatarsal, or nerve pains. If the dancer is experiencing corns and calluses, the problem may lie in the fit of the shoe. Other than changing the shoe, thin padding can be used in between the toes to protect calluses. Some of the blister bandages that are very thin and almost transparent can be used easily in the pointe shoe as well. In regards to giving the dancer some extra arch support while rehabilitating from an injury, the traditional Podiatric removable longitudinal metatarsal pad can be cut and fabricated as it will usually fit into a soft slipper, jazz, tap or character shoe.

An excellent shoe alternative for an injured dancer may be to use a jazz sneaker, which can accommodate the padding of choice, and give support to the injured area while the dancer progresses back to a full schedule.

If needed, the tap shoe, character shoe, or hip-hop sneakers will house a thin orthotic nicely. The hard Irish dance shoe is like a combination of a pointe shoe and a tap shoe being harder in the toebox, and heel counter, but very flexible through the arch. This shoe is snug and only small amounts of padding can be added. For the barefoot dancer, skin colored tape may be used for the foot or ankle during performance, but a jazz or ballet shoe with some padding accommodations is best for regular daily class until the area of injury is healed. Skin colored athletic or kinsesiology tapes can easily be hidden under socks, stockings or the shoes as needed.

Street Shoes for the Dancer

Evaluation and suggestions about street shoes should always be an important part of the rehabilitation plan. Just about every lower extremity injury will benefit from a combination of a properly supportive shoe and some form of arch aid. Instruct the injured dancer to not wear unsupportive shoes, flip flops, or go barefoot. Simple Podiatric longitudinal arch padding is very helpful and when the dancer realizes it support the foot considerably, it can signal that a custom orthotic device will work well too. It is an excellent idea to consider a custom functional orthotic device if there is a reoccurring lower extremity injury, abnormal alignment of the feet, bunions, or hammertoes developing and/or leg length discrepancies that are causing foot aliments. Making a custom orthotic device will align the dancer properly and be specific to his/her alignments, fit into most street shoes, and have good many year longevity. Whether for a young or for the professional dancer, a long standing injury will affect the dancer physically, emotionally and may affect the bottom line for a dance company or studio, if they are continually unable to dance. A healthy dancer is a happy dancer.

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Baseball and Softball

31

Tim Dutra and Mark Razzante

Baseball and softball are very popular sports at all levels of play and are considered limited contact sports. Recreational players typically have a poor level of conditioning, and many softball players will play well into their adult years. The evolution of baseball and softball cleats has basically followed the same pattern as football and soccer shoes. Surfaces are natural or artificial turf in the field and dirt or clay on the infield base paths. Metal cleats are primarily for high school, college, and professional players; however, metal cleats are allowed in some junior and senior divisions in Little League Baseball. In recent years there has been an explosion of female participation in softball leagues from youth through professional teams.

Lower Extremity Biomechanics and Considerations of Baseball and Softball

There are unique motions in baseball as compared to other sports in regard to throwing and hitting, which are complex motions. Throwing and hitting require transferring weight to achieve the maximum force and balance. Baseball and softball

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involve straight ahead sprinting, rounding bases, sliding, batting, throwing, and pitching. Sprinting involves running the bases and fielding the balls. Side-to-side movements include taking leads, running bases, and fielding balls. The feet remain neutral to give the body an increase in stability for the lower extremity to compensate for the upper body force exerted. There is also more demand on the right foot and shoe due to running on the base paths, where the shoe contacts the inside corner of the base. Pitchers also have the increased demand of pushing off during their pitching motion, so the more rigid the sole of the shoe, the better support during push off. The catcher requires more flexion in the ball of the foot as the position requires that most of the time they are in the squatting position, with weight equally distributed on both feet.

General Footwear Recommendations

As a rule when fitting shoes for athletes, the shoes should feel comfortable from the start and they should not require a break in period. Shoes offer protection, support, and cushioning for the athlete, but ill-fitting shoes will cause blisters and nail problems. Shoe characteristics and features for baseball and softball cleats should address the following [1–3]: (1) firm heel counter, (2) torsional rigidity, (3) shoe flexion in the forefoot, (4) stable upper material with hard leather preferable, (5) single density midsole, (6) external last—straight last increases control, (7) internal last—board lasted, (8) outsole with cleats usually square made of molded rubber, polyurethane-like material, or metal (Figs. 31.1 and 31.2). Some models have detachable replacement cleats. Turf cleats have shorter and more numerous rubber studded cleats, and (9) cushioning-EVA-wedged midsole increases cushioning—based on personal preference/comfort.

Lacing techniques include conventional techniques—diagonal or chevron, and parallel. Socks include cotton sanitary hose; a player may use synthetic sock underneath sanitary hose made from acrylic, polyester, polypropylene, or nylon.

Fig. 31.1 Men's molded cleat baseball shoe (Courtesy of New Balance, Boston, MA)

Fig. 31.2 Men's high-top baseball cleats with nonmetal spikes (Courtesy of New Balance, Boston, MA)

Footwear Modifications

Pathology Specific (Acute and Chronic)

Shoe and lacing considerations are the same as for general recommendations. Prefabricated insoles can provide some cushioning and support for acute or mild problems. As a general rule, the slower athletic movements require more medial support, which is best provided by straight lasted shoe. A curve lasted shoe is better adapted for faster movements which increase stress on the outer aspect of the foot. Variable width lacing is very helpful for wide or narrow foot types. Uppers are usually leather with a padded tongue and collar for comfort. A rigid heel counter is needed for support and to prevent heel slippage, as well as a soft and flexible Achilles tendon heel pad. Metal cleats usually have the split cleat with three cleats in front and two in the heel. Some models come with removable versions. Softball cleats are usually lightweight and have multi-studded cleats. Pitchers often require a toe cap for toe drag to help prevent excessive wear to the front of the shoe. Most of the baseball and softball shoes are patterned after running shoe technology, with a wider, deeper toe box, more rigid heel with Achilles pad, lacing pattern, and a sock liner/insole with more cushioning and support. Many brands and models are available to choose from—including team colors. Popular brand names include Adidas, Easton, Mizuno, New Balance, Nike, Puma, Reebok, and Under Armour, and most baseball shoes will allow adequate room for a low-profile custom foot orthosis.

Special features of baseball and softball cleats include the following:

- Ankle strap for increased lock down
- Flex grooves in forefoot of shoe
- Full-length midsole to increase cleat pressure dispersion
- Multidirectional pattern outsole for maximum traction
- Nylon pull tab in heels
- Molded EVA sock liner
- Lightweight synthetic and mesh upper combination
- Molded heel for lateral support
- Different number of spikes for traction

New Technology

For the most part, baseball and softball cleats remain unchanged, however with a constant desire for athletes to become faster cleat manufacturers continue to improve upon materials. New materials have allowed cleats to weigh in at less than 10 oz (Fig. 31.3). Rather than the traditional leather upper, weight can be shed with a more breathable mesh upper, or a mesh combination with leather or suede. Inserts comprise synthetic materials such as EVA or Lunar foam. One constant seems to be the consensus on nine spikes although each manufacturer makes modifications to flexible grooves on the sole.

Pitchers

In addition to adding a toe cap to the push off leg, the pitching position creates different pathologies. Usually the focus is on the throwing arm but the lower extremity is a big factor as well. Unique forces to pitchers compared to the rest of the team consists of a push off from the rubber, a long stride or lunge with the contralateral limb, and a hard landing force on the stride limb with a certain amount of torque upon landing. The stride or lunge leg experiences up to two times body weight in ground reactive forces upon landing, which along with rotational forces places this lower extremity at risk for more injuries than the stance limb [4]. As for softball

Fig. 31.3 adizero Afterburner 2.0 uncaged weighs only 8.7 oz [7]

pitchers, there is positive relation between pitch velocity and ground reactive forces in the stride/lunge leg [5]. Not only can this motion lead to lower extremity injuries, it can also be linked to upper extremity injuries in the abnormal foot type. The odds ratio of an abnormal foot type (pes planus or pes cavus) and a pitching arm injury requiring surgery is 3.4 if the deformity is in the stance foot and 2.9 if the deformity is in the lunge foot [6].

Catchers

Different from the rest of the fielders, the catcher routinely crouches down in a static position. In the catching position, knees, ankles, and metatarsophalangeal joints are under excess flexion or extension. Catchers may have a difficult time achieving or maintaining this position if they are victim to anterior ankle impingement, equinus deformity or hallux limitus or rigidus. These conditions prevent proper range of motion at crucial joints to the catching positions that may have as much forgiveness as the other position players.

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Soccer

32

Robert M. Conenello

Soccer is one of the most popular sports in the world. It is easy to learn, relatively safe, can be played by those of all athletic abilities, and offers equal opportunities for boys and girls.

Unlike other sports, soccer is a game of nonstop movement that requires a player to move quickly in all directions. It is also unique in that the players must use their feet to control and advance the ball.

This chapter will attempt to provide the reader with a resource for the variety of footgear available to the modern soccer player.

Lower Extremity Biomechanics and Considerations of Soccer

The soccer player is an extremely fit athlete who requires healthy lower extremities to succeed. The ability to move proficiently in all directions requires the feet to remain as close to neutral as possible. Running and sprinting in the forward and oblique directions are usually employed by all players, especially those positions attacking the goal. The skills of dribbling, maintaining control of the ball while running, and passing, as well as the inside of the foot pass, are essential at all levels of play. In order to pass, the player must balance on the non-kicking leg, bend the knee of the kicking leg, turn out from the hip of the kicking leg, look down at the ball, and then swing the kicking leg [1]. Most high level soccer players need to be able to perform these motions equally well with both feet in order to be successful.

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Soccer also requires players to maintain their balance while moving quickly and while backpedaling. Defenders use this skill by stabilizing themselves on the balls of their feet while moving backwards and side to side.

Jumping for a ball is also quite common during play. The player must be able to propel their body either up or side to side while having substantial proprioceptive abilities, while landing to prevent injuries.

The goalkeeper is unique in that he/she typically employs a low center of gravity with a wide stance ready to react in all directions.

A neutral or rectus foot type is ideally suited for the ever-changing demand that a soccer player encounters. The cavus foot type is at higher risk for inversion-type injuries due to the constant cutting, as well as the possibility of entanglement with another player while challenging for a ball. A pes planus-type foot will fatigue more quickly and leave the player more vulnerable for overuse injuries, such as plantar fasciitis and shin splints.

General Footwear Recommendations

The soccer shoe, or boot as it is commonly referred to, has evolved tremendously over the years. The surfaces on which the game is played on are varied, and as a result shoe manufacturers have created surface-specific shoes. The difficulty associated with playing soccer on different types of grounds has made it necessary for the shoes to offer proper resistance or ground traction.

Anatomy of a Soccer Shoe

In general, soccer shoes comprise two regions: the upper and the outsole. Different materials and technologies can merge to make a varied selection of shoes.

Upper Materials

The upper materials found in soccer shoes are composed of either leather or synthetic. According to Nick Romonsky, DPM, podiatrist for the United States national soccer team, “The new uppers are now better mirroring the anatomical contour of the foot. Even the heel counter is contoured for a better fit and the overall shape helps provide comfort, stability, and better ball handling.”

Leather uppers seem to be more popular with more experienced players due to their overall comfort. Carlos Alarcon of Birkenmeier in Hackensack, New Jersey, has been fitting players of all levels with shoes for the past seven years. He states “leather shoes will mold to the feet over time, and will allow for better feel of the ball by creating greater friction.” True leather shoes are classified as either full grain or Kangaroo leather. Full grain is sturdy and offers better longevity than the more specialized leathers. The most expensive leather upper is K-leather or Kangaroo leather, which is a softer product that makes the shoe feel lighter and more form fitting.

It is not as durable as full grain leather and wet weather will promote breakdown, so care should be taken to protect it.

Interestingly enough, many of the leading soccer shoe manufacturers are utilizing synthetic materials in their high end products. These shoes are manufactured with special microfiber technology. The Nike Mercurial Vapor uses Teijin fibers for this purpose. This fiber when exposed to sweat immediately becomes twice as thick for a smooth inflow of air [2]. This creates a good wear comfort depending on the condition of the wearer. The overall result of this adaptive material is increased comfort for the player.

On the opposite end of the synthetic spectrum are plastic-type shoes seen in entry level cleats. These inexpensive shoes do not allow the release of moisture, which can lead to blisters. The plastic footwear may also form a fold or crease where the foot bends which may lead to potential hot spots or blisters. It is this contributor's opinion that these types of cleats should be reserved only for the very young player who is just being introduced to the sport.

Outsole Materials

Every type of outsole material is manufactured to perform under certain field conditions. The shoe must assure good contact with the playing surface, and the sole must adapt optimally to all types of surfaces [3]. The cleat should provide the player with enough traction to prevent from slipping and allowing the opportunity to turn, stop, and accelerate easily.

Molded Shoes

These are the most common types of cleats and are best for use on firm natural playing surfaces (Fig. 32.1). The rubber or hardened plastic projections provide traction control and support. These boots are ideal for beginning and intermediate players as they can be used on most types of playing surfaces. The traditional molded shoe contains a sole that has between 10 and 15 round studs.

The bladed or x-grip design utilizes slimmer studs, strategically placed in different angles to offer a player better footing (Fig. 32.2).

Detachable Cleats

These are cleats designed for unstable or usually slippery natural surfaces. They have fewer, longer studs than a firm ground shoe, and are usually made of hard plastic or metal tips (Fig. 32.3). The type and length of the cleat can be changed depending on the weather and field condition. The reason there are fewer studs is so that mud and grass won't get trapped on the bottom of the footwear and make the soccer shoe become heavy [4].

Fig. 32.1 Molded shoe

Fig. 32.2 Bladed design

Fig. 32.3 Detachable cleats

Turfs

These types of shoes are commonly referred to as “turfs” as they are best suited for hard artificial playing surfaces (Fig. 32.4). The outside consists of multiple short rubber studs. This cleat pattern is more forgiving on the feet and body as it more evenly distributes pressure across the entire foot. These hard ground shoes are this contributor’s choice for youth soccer players since they provide adequate traction but offer the most comfort for young feet.

Referees are an often forgotten population of the soccer world that tend to be on their feet for many hours in a day. Dr. Paul Trinkoff, a Chiropractor and NCAA soccer referee, states, “ Referees can be assigned to multiple games in a single day. The large amount of running puts a huge demand on the individuals feet, no matter what the surface. It is for this reason the turf, which is somewhat of a hybrid between a cleat and a sneaker, is the shoe of choice of most referees. The turf seems to accommodate well to all surfaces without compromising comfort or support.”

Hybrid

The Adidas Tunit premium show is unique in that it is an adaptable system (Fig. 32.5). It offers three upper soles, interchangeable chassis, and all three sets of cleats for all playing surfaces and conditions.

Fig. 32.4 “Turfs”

Fig. 32.5 Hybrid

Indoor

This type of shoe is intended to be played on hard flat surfaces such as gym floors (Fig. 32.6). These low-profiled shoes usually have gum rubber bottoms with a tread patters similar to traditional sneakers. Players will often opt for this type of shoe over a turf as the soles usually offer greater ball control.

Midsole

Unlike other sport shoes, soccer cleats are made very low to the ground with minimal midsole material. This design allows the player's foot to feel closer to the ground for optimal feel and aggressive maneuverability without sacrificing comfort. The problem encountered with this negative heel design is that it can cause a greater amount of traction on the heel through a pulling force of the Achilles tendon and the plantar fascia.

Manufacturers have created many proprietary technologies built to cushion and support feet from fatigue. Some of these include an insert of low-density polyurethane or EVA placed in the sole below the heel. This feature aids in cushioning and helps protect the foot by absorbing and dissipating impact forces [5].

Lacing

Most soccer shoes incorporate a traditional lacing system as is seen in tennis shoes. Newer models utilize an innovative asymmetrical loop lacing system. These laces are oriented obliquely with a Velcro secured fold over tongue. The concept is to provide more foot to ball contact for better ball striking accuracy and ball spin.

According to Dr. Romansky, there could be potential problems associated with this lacing pattern. He states, "There may be a decrease in the stability of the upper of the shoe which may shift to the side of the lacing system. Furthermore, a lacing system placed in such a manner may interfere with a player's ability to properly put spin on the ball."

Fig. 32.6 Indoor shoe

Shin Guards

One other piece of equipment utilized by the soccer player is shin guards. These are small hard plastic guards that cover the anterior of the lower leg. Some styles of shin pads are incorporated into an anklet which also may have detachable ankle supports. The added bulk of these will affect the fit of the soccer shoe. It is for this reason that the player must be fitted for his boot with all game-related gear.

Orthoses

The use of custom-molded functional orthotic devices in a soccer shoe can be quite challenging. The fit of a soccer shoe is different from that of street shoes as they are often designed with a more narrow upper and have overall smaller volume. This leads to a very neat fit for the player. Trying to add any sort of functional insert to this shoe design can be challenging.

A soccer device should increase contact surface area under the foot, stabilizing the rear-foot and mid-foot, which influences knee alignment during rapid deceleration [6]. Such a device consists of a copolymer/crepe shell, posted with medium density crepe in the rear-foot. The heel cup is shallow at 5 mm. A 1/16″ polyfoam top cover will mold to the foot and provide a nonskid surface, even in wet conditions.

Common Injuries and Preventions

The amount of time a soccer player spends in a game is minimal compared to the hours of practice and conditioning these athletes are engaged in. While repetitive drills, running, and conditioning will make the player more proficient, it also increases the risk of injury. These ailments can be classified as either cumulative (overuse) or acute (traumatic) injuries.

Overuse injuries may present as nagging soreness that is often overlooked, but can quickly manifest into a much more serious pathology.

Acute injuries occur due to a sudden force or impact and can be quite dramatic.

Apophysitis

This is a growth plate disorder most commonly seen in the calcaneus (Severs Disease). It affects young athletes between the ages of 8 and 14 who are usually going through a growth spurt. This heel pain usually presents as a result of traction to the calcaneal apophysis from both the Achilles tendon and plantar fascia insertion. Clinical signs include compression tenderness of the growth plate on direct palpation and pain upon ambulation. The soccer cleat does not offer the player the same level of shock absorbency as a standard running shoe. It is also designed with a negative heel where the heel is lower than the toes. This causes pressure to be placed on the heel which leads to inflammation and pain.

Reducing the excessive motions of the foot in the cleat can help eliminate the player's symptoms. This is accomplished by adding a heel lift to reduce the tension on the Achilles and plantar fascia. As symptoms subside, a functional orthotic device may be fabricated to help prevent recurrence.

Plantar Fasciitis

This is an inflammation of the plantar fibrous attachment of the calcaneus to the ball of the foot. This is characterized by first step pain usually seen at medial aspect of the heel and arch. Fasciitis is exacerbated in the soccer player due to shoes with minimal arch support. An orthotic device that can decelerate pronation yet still fit comfortably in a soccer cleat will help alleviate the player's symptoms.

Achilles Tendonitis

Running and jumping on softer pitches can lead to excessive pronation. The flat soccer shoe is ill equipped to prevent these pathologic motions. As a result, increased motion above the calcaneus can cause an increased pull on the Achilles tendon. As a result, the tendon thickens and causes pinpoint tenderness proximally 4 cm above its insertion. A neoprene heel lift can be placed in the boot to decrease the tendon's pull. The player should also select cleats that have a rigid heel counter which can cradle the back of the heel. The counter should be rigid from the outside while affording sufficient internal padding.

Soccer Toe

This injury is a result of a painful jam or hyperextension of the big toe. When a player tries to pivot quickly and utilizes the hallux to perform this motion, extreme pain may result. This condition is more common on artificial turf but can happen on grass as well. Treatment includes a stiffer, hard toe shoe that fits perfectly so that the entire ball of the foot is used for turning as opposed to only the large toes.

Inversion Injuries

These injuries include lateral ankle sprains and fifth metatarsal fractures. They are often seen by direct player to player contact while challenging for the ball. Usually contact is made when the foot and ankle are firmly planted in the turf.

Improper cleat selection for the playing surface is often the culprit for these injuries. The player must select a stud pattern that will provide traction but will not sink deeply into the ground causing instability.

For patients with chronic lateral foot and ankle instability a custom-molded functional orthotic device may be used. A low-profile device with a rear-foot posted to neutral and a valgus posted forefoot may help prevent such injuries.

Conclusion

The dynamics surrounding soccer makes it imperative for the clinician to understand all of the variables involved in the modern game. A thorough evaluation of the player's shoe gear and fit and the surfaces they play on are all components that must be considered to prevent injury and increase productive participation.

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Part IV

Special Populations and Athletic Footwear

33 Pediatric Footwear

Mark Cucuzzella

Before discussing ideal footwear for children, consider normal foot development. The alignment of a child's foot and lower extremity changes in the early years. Sitting and crawling improves core strength, then they start to stand, cruise, walk, and finally run. Bones get longer and change shape. Due to the intrauterine position, newborns have a high arches, bowlegged limbs, and often in-toeing of the feet. Gravitational pull is strong enough to almost reverse this, and by age 4 children typically have a pronated foot and knock-kneed limbs. As activity increases, individual muscles get stronger. Due to continued gravitational pulls and the powerful developing muscles of children, this seemingly "malalignment" adjusts back to what would seem normal for an adult by the time they are 7–8 years old.

Here's an important point to keep in mind—a child's foot is not a miniature version of an adult's foot. In early development, a child's foot is widest across the toes. If our population wore shoes that were designed with this functional shape from birth, then most adults would also have feet with the widest part across the toes, and the toes would be perfectly aligned with the metatarsals (long bones in mid-foot). Most of a child's developing foot is composed of cartilage, which is gradually replaced by bone. If the cartilage is deformed by badly shaped or rigid shoes, the bones will take on the deformed shape. It's vital that kids' shoes allow enough room for natural growth, until the foot bones mature. This doesn't happen until ages 18–19 for girls and 20–21 for boys. Simply put, inflexible, poorly shaped shoes are potentially harmful—they restrict the natural movement and development of the foot.

Bony alignment changes are a healthy, normal, part of human development. Care must be taken when prescribing braces or devices, which may have the affect to create misalignment later in childhood. Pediatricians and podiatrists now realize that there is no single best leg alignment and to allow natural development.

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The widest part of newborn's foot is not the ball of the foot, but their toes. Adult feet in modern societies don't look the same. The narrow toe boxes in footwear have changed the alignment of our feet, just like braces were once widespread to change the alignment of the legs. Culturally a pointy shoe looks normal as does the foot shape accommodating this look. Children's shoes are often shaped to this last and thus change shape. This was demonstrated over 100 years ago in a seminal paper by Hoffman.

Children's shoes are often too stiff to allow natural movement. Materials used in the construction of adult shoes are reproduced for kids weighing a fraction as much. Children do not have the physical weight to flex these shoes. A child's foot is designed to move, and the specific strengthening of muscles aligns the bones and joints. Adults who have grown up barefoot or in minimal sandals developed very robust healthy feet with strong muscular attachments to stabilize the foot. The modern shoe-wearing adult's foot does not typically have the same strength and stability.

We are all born barefoot and if allowed to run, jump, and bound in our barefeet as children, we develop the "magic human spring," which starts at the foot [Lieberman]. When we begin to walk and run in stiff and cushioned shoes the spring gets smaller, and then with injury we are often told to run in a supportive shoes (spring getting smaller), and then with further injury we are advised to run in the supportive shoes and orthoses (spring getting smaller still).

The body will seek to find motion and impact reduction at other joints when not available at the necessary joint (the foot). In western societies we have a greatly

Fig. 10.—Foot Impressions and Tracings of Bagobo Children, Showing the Effect of a few Weeks of Shoe-wearing. A and C Before, and B and D After Shoe-wearing. Note Narrowing of Front of Foot and Change in Direction of Long Axis of Great Toe.

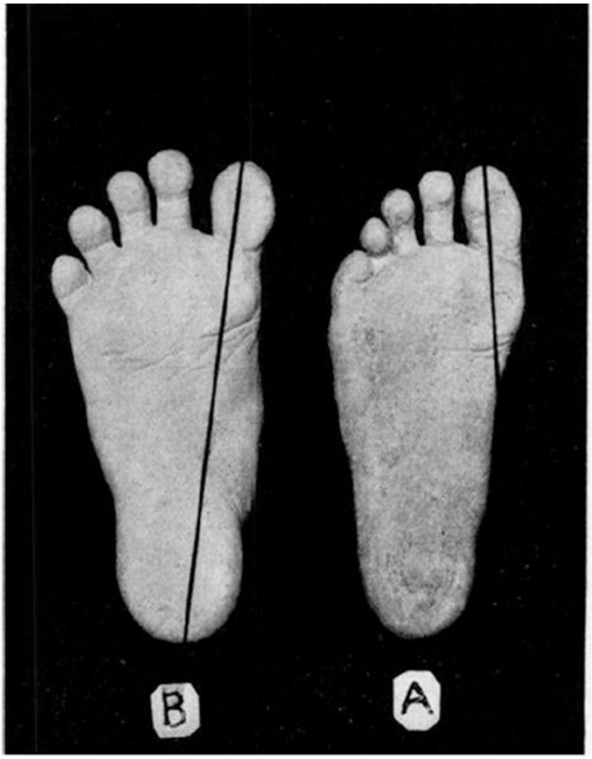

Fig. 11.—A, Photograph of Plaster Cast of Foot of Bagobo Boy that had Worn Shoes a few Months, Contrasted with B, Photograph of an Adult Bagobo that had Never Worn Shoes.

disproportionate burden of lower back pain and injury, knee and hip replacements, and impaired general mobility with aging. We detrain our spring and these joints take the load. These conditions are nonexistent in barefoot societies who walk more than we do. Can we retrain all the adults? Maybe, with patience and a progressive re-adaptation, but it may take years. Once you are walking with a cane or walker, the chances are slim.

As a family and sports physician, I firmly believe that children should play in their bare feet or in activity shoes that complement natural foot development and proper biomechanics of movement. Runners, walkers, coaches, and the medical community are all awakening to the benefits of allowing proper natural foot motion to occur in all of our daily activities. Proponents of natural running consider that the smartest design developed for human movement and injury-free activity is the human foot itself and the critical need to enhance balance.

Pediatric footwear until recently have been marketed by the shoe companies to parents, educators, and health care professionals to prepare our kids for shoes they are marketing for adults to wear. The modern shoe industry and its marketing effectively convince parents that when running, a child should wear miniature versions of traditional adult running shoes; almost all of which have elevated heels, extreme cushioning, and some form of motion control technology. Many dress and casual shoes for children are also stiff and overly supportive.

The APMA (American Podiatric Medical Association) [1] *parent flyer* states that parents should "*Select a shoe that's rigid in the middle. Does your shoe twist? Your shoe should never twist in the middle.*" It also however states that, "*Step three does not apply to toddlers shoes. For toddlers, shoes should be as flexible as possible.*"

Lieberman has discussed the affects of footwear on gait, and some recommend that children should run barefoot as much as possible, and when they need a shoe, they should wear one that allows the young foot to develop its natural strength, support, and function. Parents should reconsider that their children need "sturdy" or "supportive" shoes. As Dr. Lieberman demonstrated well in his landmark paper in Nature (Jan 26, 2010 [2]), footwear can have a large influence on natural gait.

Fig. 23: Foot inside snug-fit shoe. Whole lateral rim of metatarsals and digits are pushed in by shoe, depriving them of normal function.

A foot builds its own intrinsic support via communication with the ground, building strength and stability through proprioception, and allowing normal force loads to be applied to the areas that nature intended. Any changes from what is natural in a developing child create an adaptation and has potential for further compensation.

An elevated heel sets up upstream mechanical compensations at many upstream joints. A child's shoe that elevates the heel even as little as 4 mm puts the small foot at an angle of over 10°.

Figure 4: Perfect feet of shoeless young boys. Note straight toes and spaces between.

The limited literature on children's footwear supports the "less is more" approach.

A recent review in The Journal of Family Practice [3] concluded that flexible flatfoot does not affect function and that there was no evidence to treat it. Twenty years ago, a review of children's shoes and gait in the journal *Pediatrics* [4] outlined key factors that affect children's feet:

- Optimum foot development occurs in the barefoot environment.
- Stiff and compressive footwear may cause deformity, weakness, and loss of mobility.
- The term "corrective shoes" is a misnomer.
- Shoe selection for children should be based on the barefoot model.

On the issue of a shoes' affect on gait Wegener in 2011 [5] concluded: "Shoes affect the gait of children. With shoes, children walk faster by taking longer steps with greater ankle and knee motion and increased tibialis anterior activity. Shoes reduce foot motion and increase the support phases of the gait cycle. During running, shoes reduce swing phase leg speed, attenuate some shock and encourage a rearfoot strike pattern. The long-term effect of these changes on growth and development are currently unknown. The impact of footwear on gait should be considered when assessing the pediatric patient and evaluating the effect of shoe or in-shoe interventions."

Tudor in 2009 [6] concluded: "…no disadvantages in sport performance originating from flat-footedness were confirmed. Children with flat and children with "normal" feet were equally successful at accomplishing all motor tests; thus, we suggest that there is no need for treatment of flexible flat feet with the sole purpose of improving athletic performance, as traditionally advised by many."

An article in Gait and Posture by Wolf in 2007 titled *Foot motion in children shoes—A comparison of barefoot walking* wanted to test the hypothesis that the increased prevalence for flatfoot and hallux valgus in modern societies may be the consequence of inadequate footwear in childhood. Their study contrasted barefoot motion, motion in a thin and flexible shoe, and a more standard shoe. The conventional shoe significantly affected the motion of the foot compared with the flexible shoes. In conclusion, the authors state, "the encouraging findings with this shoe (flexible prototype) together with previous recommendations by Staheli and Maier would support the principle: *The shoe should in no other way influence the normal foot than to protect it against lesion and coldness.*"

Finally, a seminal paper in 1905 by Hoffman [7] concluded: "…feet all develop the same up until the time of wearing shoes, after which progressive characteristic deformation and inhibition of function ensue. The children of shoe wearers inherit the same foot type as barefoot races, and this type is changed only so far as foot wear modifies it. He goes on to state that flatfoot and the height of the arch of the foot are not pathological."

One example of deformation we see now in many high school runners is hallux valgus. Ill-fitting shoes with a narrowed toe box may aggravate hallux valgus. Furthermore, most runners, both young and old, cannot stabilize and balance on one foot.

The next time in a park, observe a child run barefoot. Notice the relaxed movement and foot placement. They spring. They do not strike hard on their heels. Then watch the child with the highly cushioned or supportive shoe. The difference is easy to see.

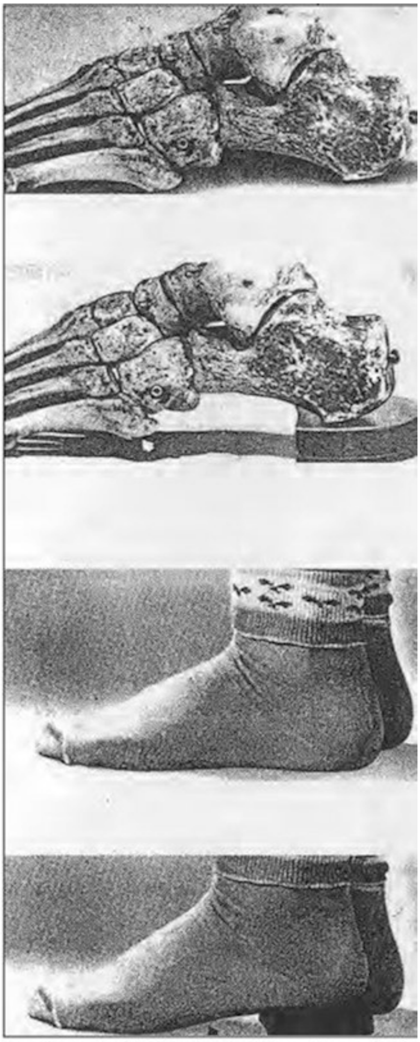

Fig. 33: Top, weightbearing function of base of fifth ray. Second, even low heel denies the ray its normal function. Third and fourth, same effect on flesh-covered foot.

So What Are the Important Features to Look for in a Child's Shoe?

- Ultrathin soles to allow proper proprioception, neuromuscular activation in the entire kinetic chain, and to complement the body's natural ability to absorb ground forces.

- Low, flat to the ground profile—shoes should allow all play activity that involves climbing, running, and jumping. Shoes should enhance lateral movement since the foot will not be up on a platform or have a slope from heel to forefoot.
- The materials should be soft and supple, thereby allowing natural foot function. The shoe should bend easily at the toe joints—this is where a foot is designed to bend to recreate the arch on takeoff.
- The toe box should be wide enough to allow natural toe spread. Foot support is created by the natural arch of the foot with the great toe stabilizing the arch. When the heel is elevated and great toe deviated toward the second toe (a common design flaw in many shoes which come to a point), this stability is compromised. The foot produces the most leverage when the toes are straight and aligned with the metatarsals. A child's foot is widest at the ends of the toes (as should an adult's be if they have been in proper shoes or barefoot).
- A single piece midsole/outsole allowing protection on unnatural surfaces (concrete, asphalt) and natural rough surfaces (rock, trail) while allowing proprioception and natural dissipation of ground reaction forces.
- Upper material should be soft, breathable, and washable.
- Get over the notion that shoes need "traction." In a moving child the more stickiness and grip, the more heat produced in the foot and braking moments on running activity.
- Discourage the use of thick, heavy socks as these interfere with foot proprioception.
- All efforts should be made to use recycled materials in the construction of the shoe.
- Shoes should be a good value and of comparable price to other children's shoes.
- Design and colors should inspire fun and play.

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34 Special Olympics: Custom Foot Orthoses for Athletes with Genetic Disorders

Patrick Nunan and Shawn Walls

Mentally and physically handicapped individuals, such as those afflicted with Down syndrome and cerebral palsy, have gait problems that progress with age. These gait abnormalities frequently lead to the eventual development of foot pain if not corrected. No matter what the etiology, foot pain can lead to a decrease in activity and mobility and, for the mentally handicapped, the eventual removal of community participation [1]. Studies have found that early identification and correction with conservative care of lower extremity foot deformities commonly seen with the mentally and physically challenged can lead to improved development of the individual both physically and socially [2, 3]. This chapter covers orthoses, shoe gear, and shoe modifications to help with the most common pedal problems associated with active mentally and physically challenged individuals, with the hope of improving physical activity and wellness.

In 1948, Sir Ludwig Guttman held the first organized sporting event for the physically handicapped. The Paralympic Games, founded by Guttman, included athletes with visual and physical impairments, such as those with amputations and those requiring wheelchairs [4, 5]. Other programs have since been created that allow for the participation of a wide variety of athletes, including those with mental and physical disabilities, in national and international competition. One of the most noted organizations today is the Special Olympics. The Special Olympics is dedicated to providing training for 2.25 million mentally challenged athletes in 160 countries, promoting improvement in both physical and mental fitness [6]. In the United States, there are an estimated two to three million active athletes with mental and physical disabilities [5].

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There is a vast volume of literature covering the physical improvements that exercise and physical activity can have on the human body. This literature mainly covers normal developing adults. Little research has been generated for the physically and mentally handicapped active population [4]. The small amount of research that has been conducted is dedicated to showing that with an increase in activity and interactive events such as sports, mentally and physically handicapped persons show improvements in daily activity, health, and social interactions [3–5, 7].

Before a handicapped individual participates in athletic events a thorough physical should be performed to assess physical limitations. Athletes with mental and physical challenges can have physical limitations and health risks that are non-conducive to certain athletic events. Physical limitations that should be considered before participation in individual sporting activity include endurance, strength, and mobility. Severe health risks, including those that can cause loss of body control or even death, need to be identified. For instance, in individuals with Down syndrome up to 25% have atlantoaxial instability from ligament laxity. Increased ligamentous laxity can allow subluxation of the C1 vertebrae on the C2 vertebrae. Vertebral subluxation will cause compression on the spinal cord by the dens. Spinal cord compression can present as abnormal neurological manifestations, quadriplegia, and death [1, 8]. In individuals with cerebral palsy, 40% of all children have an associated seizure disorder [3]. Seizure disorders need to be identified, addressed, and monitored by a medical professional before athletic clearance can be given.

A brief discussion on normal gait and development of the lower extremity is warranted. During a normal child's growth the lower extremity rotates inwards and outwards around a central axis at three key osseous locations: the hip, knee, and ankle. The rotation is caused by a balance of soft-tissue development and growth of long bones. There are three key periods of growth that occur at approximately ages 1, 6, and 15. At each age the bones of the hip, knee, and ankle are rotating either inward or outward, ultimately causing the foot to retain an inward or outward position. Key rotating bones are the femur, fibula, and tibia at the tibial condyles and malleoli. Differences in femoral and tibial bone rotation result in bringing the knee into a progressively decreased varum position, rotating the knee inwards, and bringing the knees closer together throughout skeletal maturity. At the ankle, the external malleolar position increases with age.

The result of the combined bone rotation at all levels of the lower extremity causes out-toeing or an externally rotated flatfoot from 0 to 2 years old. Flat foot and out-toeing can be considered normal from birth to 2 years old as a child will be unable to form a foot arch due to lack of maturity of the neurological system until after age 2. Intoeing, or "pigeon toe," will be present from 4 to 6 years old and again at 13–15 years old. At the age of skeletal maturity, 15–18 years old, the malleoli should be rotated 18–23° of external rotation forming the normal mildly everted foot position of about 18° from the body's sagittal cardinal plane [9].

Common foot problems affecting normal gait can be classified into three general categories: pes planus, pes cavus, and equinus. These pathologies are the result of one or a mixture of three main biomechanical mechanisms: pronation, supination, and ankle equinus. Other problems commonly associated with mentally challenged athletes include hyperhidrosis syndromes.

Ankle equinus is the inability of the foot, at the ankle joint, to dorsiflex 10° past perpendicular to the leg. It is a common deforming force in the foot, typically causing the foot to pronate. Pronation is a frequent biomechanical compensation in normal gait. Primary manifestations of ankle equinus without biomechanical compensation, such as tiptoe walking, are not commonly seen except in certain neuromuscular diseases such as muscular dystrophy and cerebral palsy. Conservative treatment for ankle equinus consists of intrinsic and extrinsic heel lifts and will be discussed with the conservative treatments of pes cavus and pes planus.

Pes planus, or flat foot, is one of the most common foot conditions globally [10]. Flexible flat foot has been shown to occur in 44% of children aged 3–6 years [11]. Some experts consider flat foot a normal developmental stage in children up to 6 years old [12]. The most common cause of flat foot is excessive pronation at the subtalar joint.

Pronation of the foot inhibits mechanical dampening mechanisms by the bone and soft tissues, preventing internal rotation of the leg during heel contact and leading to foot and joint pain. Pronation is considered to be the foot at the subtalar joint functioning at maximum eversion. Quantitatively pronation can be described as a measurement equal to or greater than 10° eversion at the subtalar joint, leaving the calcaneus in a valgus position [8, 13].

Pronation can be visually identified in several ways: (1) an everted heel; (2) flat medial arch on or off weight bearing; (3) prominent talar head or midtarsal bones; (4) the inability of the heel to supinate with performance of the Jack's test or Hubscher maneuver, activating the windlass mechanism to form the medial foot arch; (5) forefoot abduction causing "too many toes sign" on weight-bearing evaluation; and (6) the lateral border of the foot appearing shorter than the medial border [13, 14]. Appearance of a midtarsal bony collapse with a pronated foot is usually an indicator of more severe pes planus problems [13]. The degree of abnormal pronation leading to pes planus depends on a variety of factors.

Flat foot disorders can be classified as either pathologic or physiologic. Pathologic disorders are commonly seen at birth and cause rigid abnormalities. Examples of pathologic disorders include vertical talus syndrome, trauma, and spastic conditions. Physiologic disorders result from developmental abnormalities that cause a foot to gradually lose an arch throughout the first decade of life [11, 14].

Pes planus etiologies can be further classified as either genetic or acquired. Acquired pes planus is seen with (1) osseous fractures, (2) ligamentous tears, (3) muscular imbalances, (4) degenerative joint diseases, and (5) postural problems, resulting, for example, from obesity or pregnancy [10]. Genetic etiologies include (1) tarsal coalition; (2) obliquity of the ankle joint, where the medially located tibia grows faster than the fibula; (3) failure of tibial torsion; (4) Achilles tendon shortening; (5) ligamentous laxity (which is seen in Down syndrome, Ehlers-Danlos syndrome, and Marfan syndrome) [10, 15]; and (6) increase or decrease in muscle tone, which can cause more complex forms of pes planus. Low muscle tone is seen in neurologically delayed subjects with or without anterior horn loss, in primary muscle damage and in collagen pathology. There is debate on whether latent cognitive and neurological system development of the cerebellum has an impact on abnormal physiological development causing ligamentous laxity, such as that found in Down syndrome. It is general consensus that a delay in cerebellar development does delay the age at which ambulation begins [1, 16].

High muscle tone pathology causing flat foot is seen with spastic peroneal muscles, the primary cause of a progressively rigid flat foot [8, 10, 13, 17]. Flat foot caused by peroneal spasticity can be corrected with a scaphoid pad, varus heel wedge, and orthosis [8].

Osseous developmental problems resulting in pes planus include acetabular dysplasia, hip dislocation syndromes, metabolic syndromes such as Blount's disease, and physiological tibial varum [3, 7, 13]. These pathologies should be treated by surgical means. Foot pathologies include metatarsus adductus, hallux valgus, metatarsus primus varus, ligamentous laxity, joint hypermobility, foot and ankle equinus commonly caused by a tight Achilles tendon, pes cavus, forefoot supination, rigid forefoot varus, tarsal coalition, and foot rigidity [2, 16]. Most foot pathologies resulting in pes planus can be treated with appropriate shoe gear as long as the pes planus has not progressed to a symptomatic rigid state [7, 14].

Of the genetic disorders with associated flat foot, Down syndrome is the most common. It occurs in 1 in 660 live births [1, 2]. Down syndrome individuals are active and commonly participate in athletic events. Half of all people afflicted with Down syndrome have gait abnormalities appearing as gait imbalance and abnormal walking posture [1, 2]. Problems with ambulation are attributed to a delay in neurological development, ligamentous laxity, and muscular hypotonia, all of which are found in 88% of individuals with Down syndrome [1]. Ligamentous laxity and muscular hypotonia also allow for joint hypermobility causing increased foot width and potentially disabling osteoarthritis leading to rigid foot deformities if left untreated [1, 2, 16]. Flexibility, ligamentous laxity, and muscle hypotonia associated with Down syndrome decrease greatly with age but never fully resolve [1, 16].

Down syndrome individuals are also affected by osseous variations in bone torsion in the lower extremity. Developmental deformities include hip retroversion causing severe external rotation in hip flexion and extension and resulting in an out-toe gait. Hip dysplasia and dislocation can also be found; these are treated surgically. Knee problems are generally secondary to foot abnormalities. Knee pathology, which is relatively uncommon, includes patellofemoral instability, patellofemoral dislocation, knee flexion contracture, external tibial rotation, genu valgum, and rotary tibiofemoral subluxation. Knee pathologies are generally not inhibitory to activity or gait and tend to be well tolerated. Treatment consists of wearing a patellar sleeve during ambulation. At the ankle, the tibia is externally rotated causing an externally rotated foot [1, 7]. Although these examples of lower extremity problems are seen with Down syndrome, they are not limited to it and can found in other congenital pathologies [18].

Any deviation from normal development of the lower extremity will decrease the efficiency of gait in an active individual. Gait alteration with conservative measures that provide biomechanical and postural correction can dramatically improve activity and structural development in the lower extremity [2, 18].

Biomechanically, flat foot is a complex deformity. Pes planus can be caused from biomechanical imbalances in one body plane or a combination of all three: sagittal, transverse, and frontal. For pes planus treatment to be successful it must be addressed on the deformity's main cardial plane [13, 17].

Structurally the foot is designed to bear weight on the rearfoot, lateral column, and first and fifth metatarsal heads [10]. In pes planus, as the medial foot arch collapses the foot shifts laterally along the lateral column shorting it and lengthening the medial column. The forefoot is hypermobile, allowing the first metatarsal to shift dorsally and medially, transferring weight further up the medial column which is not designed for weight bearing. The first metatarsal and sesamoid bones normally support 33% of the body's weight during the normal stance phase. This percentage of weight bearing decreases with abnormal pronation, resulting in increased weight bearing in other areas of the foot [10].

In pes planus the rearfoot does not supinate on the forefoot, preventing locking of the midtarsal joints. If the forefoot joint complex is unlocked it is unstable. An unstable foot platform decreases the effectiveness of gait and allows joint subluxation to occur. Repetitive subluxation will result in eventual degenerative joint disease, foot pain, and possibly rigid foot deformities. Flat foot deformities that become painful and symptomatic are referred to as pes planovalgus deformities.

There are two modes of thought about correction of flat foot deformities during early limb development. Some practitioners theorize that flexible flatfoot should be left alone. The rationales are that only 20% of infants with flexible flat foot will not outgrow the deformity within the first decade of life, tight Achilles tendons can be stretched, and most flatfoot individuals do not become symptomatic [14, 18].

Other practitioners theorize that flexible flatfoot should be treated aggressively by using casting techniques and orthoses. These authors point out that there is no way to determine which individuals will outgrow their flat foot deformity; therefore prophylactic treatment should be performed before the occurrence of possible latent pathological symptoms that require difficult conservative or surgical treatment [1, 8].

With genetic etiologies like Down syndrome and others involving low muscle tone and ligamentous laxity, these factors do not resolve with age. The individual will not outgrow their pes planus deformity and will eventually develop a painful, rigid symptomatic flat foot.

Regardless of the etiology of flatfoot, methods of conservative care remain the same. Conservative treatment options used for active individuals include shoes with or without intrinsic and extrinsic modifications; bracing; and orthoses. Treatment should also include consideration of the appearance of the prescribed device. People with mental handicaps have a sense of style; thus shoes and shoe modifications have to be cosmetically acceptable [1].

Casting therapy should be employed before the child can ambulate or during crawling age and will not be discussed.

The foot and associated pathologies need to be evaluated before appropriate conservative treatment is selected. Rigid foot types need shoes that will provide smooth ambulation such as a rocker bottom sole. Flexible foot types need shoes with a mixture of rigidity and flexibility along with a sturdy shoe upper. If there is an associated drop foot or muscle hypotonia due to neuromuscular conditions, bracing needs to be considered. Width and depth of the shoe must be evaluated to accommodate a wider foot type and for use of orthoses [8]. Special shoe modifications and orthoses should be employed after independent walking starts.

Shoes in general should have a strong heel counter, inflexible rearfoot and midfoot, and a forefoot which should be flexible at the metatarsal heads. The shoe upper should have sufficient strength to hold the foot in alignment [8]. For mild flat foot with younger children, a rigid shoe should not be used. The flexible foot will not conform to the shoe shape; instead it will bend around the shoe's rigid construction, eliminating the supportive effect. For mild pes planus, a standard last, leather shoe without a rigid shank but with a firm heel counter should be used. This combination will allow for foot flexibility needs while still maintaining biomechanical control [8]. For rigid deformities the sole should have a rocker bottom to allow a smooth transition from rearfoot to forefoot, forefoot clearance at toe off, and better propulsion.

Trying to alter the shape of a developing foot with alternative shoe lasts should be performed at an early age, well before bony maturity. The theory behind early conservative care is that if the foot is held in an anatomically correct position before epiphysis closure, the soft tissue supporting the bone will alter accordingly [8]. For patients with hypotonia and ligamentous laxity, a straight last, open-toed shoe with a rigid heel counter and a rigid, wide, flat sole should be used. The straight last shoe can be further enhanced using an orthotic [1].

Further biomechanical stability can be accomplished by using high-top shoes for ankle instability. Shoe sizing should be done at the end of the day when ligaments are at their most lax. If orthoses or bracing are to be used, it is important that the shoes have removable insoles and are able to accommodate the orthotics or bracing. Shoe insoles should be replaced with the orthotic to allow for proper shoe fit. To maintain the best limb alignment in pes planus, the choice of wide flat-soled shoes increases the available weight-bearing surface, allowing for better propulsion for individuals with a potentially unsteady gait such as is found in Down syndrome [1].

Shoe modifications can be classified into intrinsic and extrinsic modifications. For young children with a mild to moderate flat foot that displays prominent midtarsal bones, notably the talar head, a scaphoid pad can be used. Thickness of the pad depends on the talar head prominence and ranges from 3/8″ to 5/8″. The pad elevates that talar head back into bony alignment. If the foot is in severe pes planus a longitudinal felt or foam pad can be placed along the medial arch [8]. Extrinsic modifications include a Kirby heel skive, a special triplanar wedge, which acts as a medial rearfoot varus wedge when placed in the rearfoot of a shoe. The Kirby heel skive causes the calcaneus to maintain an inverted position and helps prevent eversion of the calcaneus through the contact and stance phases of gait. A neoprene medial buttress can also be placed on the outsole of a shoe to allow for an increase in weight-bearing surface and shoe stability [1].

Heel cups and heel lifts can be added to shoes or orthoses, providing more STJ motion stability and bringing the ground to the heel to correct ankle equinus or limb-length discrepancy. A heel lift can be intrinsically or extrinsically incorporated into an orthotic or shoe. If the limb-length discrepancy is at or over 2 cm, the heel lift should be made as an extrinsic orthosis modification or incorporated into shoe modification. Other extrinsic shoe modifications include insole varus heel posts and rocker bottoms [1]. Shoes with layered midsole construction are better for creating intrinsic shoe modifications.

Orthoses are classified as either functional or accommodative. Accommodative orthoses are designed for pressure offloading in stance phase only and for minimally active individuals. Functional orthoses are designed for biomechanical correction during activity. They have a rigid heel counter, limiting calcaneal movement and thus subtalar joint motion. Modifications that can be performed for increased biomechanical efficacy include flares, deeper heel cups, and intrinsic and extrinsic corrective posting.

Functional orthoses can be prefabricated or custom molded. Prefabricated insoles, such as Spenco and Powerstep, provide a low-cost alternative for biomechanical correction of pes planus. Prefabricated insoles do not provide the level of support that custom orthoses can provide but they will provide an improvement in the support of a properly fitting shoe [1]. Prefabricated insoles also offer a low-cost alternative for individuals who do not perform athletic activities on a routine basis.

Custom foot orthoses should be created from a cast of an individual's foot, not from Styrofoam foot impressions. Styrofoam impressions or similar materials can create an improperly fitting orthosis due to lack of control of the subtalar joint while obtaining the foot impression [1]. A foot cast should try to precisely capture the foot in subtalar joint neutral with possibly a mild to moderate pronatory exaggeration of the heel in the biomechanically corrected position. The success of orthosis treatment is inversely proportional to the rigidity of the foot deformity. For more rigid deformities, bracing should be used to hold the deformity in place rather than altering biomechanics [13].

Three types of custom foot orthoses are generally recommended for pes planus in individuals affected with Down syndrome: leather; rigid polyolefin; and polypropylene orthoses from the University of California Berkley Laboratory (UCBL).

Leather orthoses tend to be the most accommodative fit for a variety of athletic shoes. Leather orthoses are pliable and adjustable and will expand and compress to accommodate a variety of shoe widths. Leather orthosis expansion provides comfort in tighter shoes and orthosis compression offers more support. To improve biomechanical function, leather orthoses should be four ply, have a deep heel cup, and have high medial and lateral flanges [1].

Rigid polyolefin offers the best biomechanical support by providing exceptional pronation control. It tends to be the least forgiving biomechanically if casting and manufacturing are performed incorrectly. Rigid polyolefin orthoses that are too wide will subtract from shoe support due to their inability to offer lateral compression. Those that are too narrow will irritate the foot from the creation of abnormal pressure points [1].

UCBL orthoses are best suited for individuals with severe flexible flat foot deformities such as those seen with Down syndrome. UCBL orthoses are rigid and thin, provide the ability to create a very deep heel cup along with high medial and lateral flanges, and allow for some lateral compression [1]. For severe pes planus cases, an addition of a plastic heel cup with medial arch extension can be used for biomechanical correction to a UCBL orthosis. These orthosis modifications may not be effective for individuals 12 years or older [8].

Patients with pes planus deformities from hypotonicity and ligamentous laxity may not be biomechanically controllable until skeletal maturity when hypotonicity and laxity decrease. During this time, supramalleolar ankle-foot orthosis (SMO) or ankle-foot orthosis (AFO) should be considered. AFO and SMO can promote foot control in all three body planes [13].

Some practitioners feel that supramalleolar ankle-foot orthoses offer little advantage over properly fitting shoes and orthoses. Furthermore, supramalleolar ankle-foot orthoses may need modified shoes for a correct fit [1]. Due to the limited advantages that a supramalleolar ankle-foot orthosis may provide, an ankle-foot orthosis should be considered for severe flexible or rigid pes planus. Ankle-foot orthoses can be non-articulated or articulated, generally at the ankle joint, to allow for sagittal plane motion. Ankle-foot orthoses can provide excellent control in all three body planes. Modifications include a proximal extension for sagittal plane control, anterior extension to limit transverse plane malposition, and high medial and lateral flanges with extensions from the plantar aspect of the device to the digits to help control subtalar joint pronation. AFOs are designed to hold a lower extremity deformity in a static position rather than altering biomechanical motion [13].

Pes cavus is another common foot abnormality associated with active individuals and athletes. It is biomechanically defined as the rearfoot being dorsiflexed on the forefoot, the forefoot being plantarflexed on the rearfoot, or a combination of both occurring in the midfoot. The overall result is a plantarflexed forefoot on the rearfoot.

Pes cavus deformities occur predominantly in the sagittal plane, with a majority occurring in the forefoot. Forefoot deformities are frequently referred to as forefoot equinus or pseudoequinus. Ankle equinus is another common associated deformity found with pes cavus. Of individuals affected with pes cavus, 66–75% have an associated neuromuscular disease [17, 19].

Pes cavus appears visually as a high medial arch which may reduce with weight bearing. If a high arch remains during weight bearing, the deformity is typically more rigid in nature. Pes cavus can be associated with either pronation or supination depending on foot flexibility and involvement of ankle equinus. Typically the rigidity of a frontal plane deformity and the severity of ankle equinus affect whether the heel maintains neutral, inverted, or everted position on weight bearing [17]. It is not uncommon for the cavus foot to be supinated off weight bearing and pronated upon weight bearing.

Forefoot pes cavus with normal foot pathomechanics, and without progressive muscle disease, has six typical forms: flexible forefoot varus or valgus, rigid forefoot varus or valgus, and plantarflexed first ray that is flexible or rigid. Each form will cause a high arch either on or off weight bearing. Flexible deformities will usually cause pronation on weight bearing.

Supination is defined as an inward roll of the foot during gait [19].

Biomechanically a supinated foot maintains a plantarflexed, adducted varus position. If the subtalar joint remains in a varus position during the contact and stance phases of gait, biomechanical dampening mechanisms are prevented. Without biomechanical dampening, increased joint subluxation will occur, causing osteoarthritis and spasticity of the muscles trying to maintain biomechanical stability.

While supination can cause biomechanical faults, the mixture of pes cavus, ankle equinus, and self-perpetuating myostatic contracture can cause excessive pronation in physically handicapped individuals such as those afflicted with cerebral palsy. The excessive pronation results in an equinovalgus foot orientation during ambulation, resulting in joint destruction throughout the foot. The additive effects of abnormal biomechanics plus the progressive nature of muscle contracture and increase in foot rigidity further found in neuromuscular disease aid abnormal physiological positions, making orthosis management eventually inadequate as a treatment. Individuals with progressive neurological physical handicaps ultimately require management through bracing techniques that attempt to hold the extremity in a stable, static position [13].

Pes cavus is often the first sign of neuromuscular conditions. Conditions associated with pes cavus can be acquired or genetic. Acquired diseases include spinal cord tumors, spinal cord lesions, and syphilis. Genetic diseases that cause pes cavus are typically neuromuscular in origin and include Charcot-Marie-Tooth disease, Friedreich's ataxia, poliomyelitis, progressive muscular dystrophy, and cerebral palsy [9, 17].

The most noted neurological condition associated with pes cavus is cerebral palsy. Cerebral palsy is the result of malformations in the central nervous system during gestation or immediately after birth [9, 20]. The ratio of children born with cerebral palsy is 1–5 per 1000 live births [3, 20]. There are six types of cerebral palsy, each described on the basis of associated pathological movement relating to muscle spasticity, balance, motor control, and weakness [5, 9]. Cerebral palsy types include spastic, athetoid, ataxic, rigid, tremor, atonic, and mixed [9, 17]. Cerebral palsy is further grouped by associated anatomical patterns which include quadriplegia, diplegia, hemiplegia, and others [5].

The most common form of cerebral palsy is spastic cerebral palsy, encompassing 70% of all cases [9]. Spastic cerebral palsy individuals have abnormal and primitive reflex patterns and atypical increase in muscle tone, which affects ambulatory gait as well as balance, posture, and movement [3, 19]. Cerebral palsy is a nonprogressive neuromuscular disease, but due to muscle spasticity and a tendency towards inactivity, progressive rigidity often occurs as an individual becomes older [3, 9, 17, 20]. Sports activity, routine physical therapy, and stretching can reduce the progression of muscle weakness, muscle spasticity, and rigid deformities [3].

Gait patterns vary depending on the cerebral palsy type. In spastic diplegia cerebral palsy the lower extremity has exaggerated knee flexion, increased hip adduction and internal rotation, and associated ankle equinus. With spastic hemiplegia cerebral palsy the hip and knee are either fully flexed or extended and the foot remains in ankle equinus on the affected side [19]. Other associated deformities affecting the lower extremity include hip instability, patellofemoral chondromalacia, metatarsalgia, bunions, and hammertoe deformities resulting from extensor tendon substitution compensating for ankle equinus [5].

Spastic cerebral palsy individuals are able to walk and run, though gait techniques are modified. Individuals with cerebral palsy increase their gait velocity through increasing cadence rather than stride length. This is attributed to spasticity, contractures, and muscle weakness throughout the lower extremity. Running cadence is conducive with the normal anatomical posture of spastic cerebral palsy patients with their natural tendency for hip extension, knee flexion, and ankle equinus giving the appearance that they can run better than they walk. Nonetheless, the running style used by cerebral palsy patients has been found to be biomechanically inefficient [21].

Injuries to athletes with spastic cerebral palsy are generally caused from stress-induced disorders created by trying to overcome the limitations of contractures, spasticity, and muscle weakness [5].

Conservative treatment revolves around preventing progression of contractures and loss of muscular strength. Minimal loss of strength can result in large deficits in activity, impacting mobility and independence [5]. Standards in conservative care include stretching, strength training, physical therapy, shoes, orthoses, and bracing.

Shoes are generally used in conjunction with orthoses and brace management and are not a primary treatment for moderate to severe pes cavus and rigid foot deformities. For mild flexible pes cavus, a running shoe with a higher arch support and a strong heel counter should be considered. Shoe design must be wide and deep enough to accommodate orthoses. The midsole should be layered to allow for intrinsic varus or valgus modifications and for incorporation of heel lifts to treat ankle equinus. The entire sole of the shoe can also be elevated in the case of limb-length discrepancy. For the individual with a dyskinetic, spastic, or equinus gait, modifications such as rocker bottom soles may be incorporated to allow for ground clearance at toe off.

Orthosis management is good for both flexible and mild, rigid pes cavus. A weight-bearing evaluation should be performed to identify pronation or supination compensatory factors and orthotics should be designed accordingly. Orthosis design is intended to bring the ground up to the foot, keep the foot in biomechanical correction, and, with neuromuscular disease, try to prevent the progression of contractures [13]. With progressive muscle spasticity, as seen with cerebral palsy, orthosis therapy will eventually become inadequate. Orthosis therapy used in neuromuscular disease is designed to improve ambulation and function, but also to delay inevitable surgical intervention [22]. In active individuals with neuromuscular disease the functional status of the foot is already impaired limiting the benefits of functional orthosis. Orthoses tend to be designed as a soft accommodative device to offload areas of abnormal pressure.

Orthoses can be modified similar to that of pes planus, with intrinsic or extrinsic varus or valgus wedges, medial or lateral flares, and heel cups with or without heel lifts to compensate for ankle equinus. As with pes planus, the heel lift should be incorporated into the orthosis intrinsically if under 2 cm and extrinsically if over 2 cm.

For individuals with moderate and inflexible pes cavus deformities, supramalleolar foot-ankle orthosis may be employed. Some practitioners argue that supramalleolar foot-ankle orthoses do not offer enough biomechanical support for individuals with neuromuscular disease; they instead promote the use of ankle-foot bracing [13].

Most individuals afflicted with neuromuscular disease will eventually need bracing orthoses. Orthosis bracing's primary function is to keep a lower extremity deformity in a static state. When utilizing bracing for individuals with neuromuscular disease such as cerebral palsy, movement should be incorporated to prevent muscle group weakness and progression of muscle spasticity. Common bracing includes ankle-foot orthosis and dynamic ankle-foot orthosis (DAFO). The DAFO is a thinner and more flexible brace than a regular AFO and allows for ankle joint plantar flexion. AFOs are commonly used as conservative treatment in individuals affected with diplegic and hemiplegic spastic cerebral palsy [19, 22]. Studies have shown that AFOs can improve stride length, increase velocity, and allow single-limb support in young adolescents, but the improvements degrade with age becoming nonbeneficial in one study after age 7 [19, 22]. After adolescent years AFO and DAFO are used to hold static deformities stable, reduce muscle tone during weight-bearing situations, offload pressure points, and allow for greater freedom of movement by reducing the effort required for movement [20].

Hyperhidrosis is the final subject matter to be covered. Mentally handicapped athletes and children in general have excessive foot perspiration, called plantar hyperhidrosis. The cause of hyperhidrosis is unknown [23]. Up to 5% of the general population is affected by primary focal hyperhidrosis or excessive sweating [23, 24]. Plantar hyperhidrosis tends to cause moist socks and shoes along with foot odor which can socially impact a patient [23].

There is no conservative treatment for plantar hyperhidrosis that is completely effective. Various conservative treatments for plantar hyperhidrosis can be added to one another for increased results. Frequent changing of socks and shoes is a common and effective treatment. Using alternative sock material such as rayon and nylon which do not retain moisture but allow easy passing of moisture through the material is a viable option. Using nonabsorptive material along with absorptive power, such as talc, and/or antiperspirants, such as Drysol, or roll-on deodorants with antiperspirants, can help prevent sweating and absorb excess moisture.

Individuals with mental and physical disabilities involved with sports can benefit from conservative care. Whether or not these individuals are international athletes or active amateurs, the benefits of exercise and daily social interaction can be immeasurable. Without treatment, many of these individuals will eventually develop pedal pathology, limiting or eliminating participation in physical activities. Any removal of activity can greatly impact the physical and social health of mentally and physically handicapped individuals. The use of conservative management can effectively delay, reduce, or prevent the progression of lower extremity pathology.

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Part V

Durable Medical Equipment and Coding in Sports Medicine

Durable Medical Equipment and Coding in Sports Medicine

35

Tony Poggio

Introduction

The use of durable medical equipment (DME) is a common part of a sports medicine practice. Proper documentation and billing protocols must be followed to insure proper payment and to attest to medical necessity and reasonableness of the item(s) dispensed. Medicare covers certain durable medical equipment, prosthetics, orthoses, and supplies (DMEPOS) items. Items are covered for both chronic and acute conditions (i.e., post-op) as long as the coverage criteria are met. Other insurance carriers have their own specific policies regarding coverage of DME items.

In this chapter, we discuss common DME items utilized in a sports medicine practice and insurance company coverage and billing protocols of these items.

To begin with you must determine if you even want to dispense DME from your office. As a DME provider, you are classified as a supplier not a physician. There are insurance company, state, and federal rules and regulations you need to be aware of and comply with. Space issues may also be an issue to adequately stock the various products, sizes, etc. Staff needs to be trained to explain, fit/dispense, and ultimately bill properly for the various products. For any DME item, you need to be aware of coverage issues, deductibles, co-pay/co-insurance, and any restrictions. Some items may have a specific exclusion when prescribed for the foot (as is common for foot orthotics), or only allowed for certain diagnosis, i.e., covered for tendonitis but not neuroma and covered only for the diabetic patient.

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Definition

Each carrier defines DME per their contract provisions. Furthermore the carriers will define what they will cover and under what circumstances. *This is where clear and thorough documentation in your chart is critical to ensure that the carrier understands what you are requesting and why so that it can make an accurate coverage determination according to its policy.*

CMS defines DME as any equipment that provides therapeutic benefits or enables the member to perform certain tasks that he or she is unable to undertake otherwise due to certain medical conditions or illnesses, and

(a) Can withstand repeated use
(b) Is primarily and customarily used to serve a medical purpose
(c) Generally is not useful to a person in the absence of an illness or injury
(d) Is appropriate for use in the home but may be transported to other locations to allow members to complete instrumental activities of daily living, which are more complex tasks required for independent living

All requirements of the definition must be met before an item can be considered to be durable medical equipment.

(A) Durability: An item is considered durable if it can withstand repeated use, i.e., the type of item, which could normally be rented. Medical supplies of an expendable nature such as lambs wool, pads, ace bandages, and elastic stockings are therefore not considered "durable" within the meaning of the definition. There are other items, which, although durable in nature, may fall into other coverage categories such as braces, prosthetic devices, artificial arms, and legs.
(B) Medical Equipment: Medical equipment is an equipment, which is primarily and customarily used for medical purposes and is not generally useful in the absence of illness or injury. Dispensement of such equipment may require documentation to determine medical necessity. This is based upon the standard of care and carrier policy guidelines. If the equipment is new on the market, obtaining prior authorization is recommended to obtain information from the supplier or manufacturer explaining the design, purpose, effectiveness, and method of using the equipment in the home as well as the results of any tests or clinical studies that have been conducted.

Medically Necessary

Durable medical equipment is considered **medically necessary** when ALL of the following criteria are met:

- The requested item has not otherwise been identified as not medically necessary or investigational/not medically necessary by a specific policy guideline/restriction.

- There is adequate documentation in the medical records or in the claim submission of ALL of the following:
  - The documentation substantiates that the physician exercised prudent clinical judgment to provide for a patient for the purpose of preventing, evaluating, diagnosing, or treating an illness, injury, disease, or its symptoms, and that are in accordance with generally accepted standards of medical practice.
  - There is a clinical assessment and associated rationale by the doctor for the requested DME in the home setting.
  - There is documentation substantiating that the DME is clinically appropriate for the patient diagnosis in terms of type, quantity, frequency, and accepted by community standards as being effective for that patient's condition.
  - The documentation supports that the requested DME will assist, restore, or facilitate improvement in the patient's ability to function better in normal day-to-day activities.
  - The requested DME is not primarily for the convenience of the patient.
  - The DME is not more costly than other options/items which may be equivalent as far as effectiveness and therapeutic outcome are concerned.

Not Medically Necessary

Any item that does not meet the above criteria would not be considered medically necessary and reasonable. Carriers may impose other restrictions affecting what is medically necessary and

- The DME item is intended to be used for athletic, exercise, or recreational activities as opposed to assisting the patient in day-to-day activities; or
- The DME includes an additional features that are added primarily for the comfort and convenience of the member (e.g., multiple pairs of orthoses, customized options on wheelchairs, crutches); or
- The DME item represents a product upgrade to a current piece of equipment that is fully functional or replacement of a device when the DME can be cost-effectively repaired.

Licensure

For Medicare you must have a separate DMERC license to dispense DME from your office. If you do not have a valid DME license, you can not dispense and bill the patient for a covered item, <u>even if the patient agrees to pay you for it.</u>

In the DMERC system, a physician is referred to as a "supplier." You may choose to be a "participating supplier" or a "nonparticipating supplier" under DMERC. This decision is linked to your current participation status under Medicare Part B. You cannot be a "participating" physician under Medicare Part B and a "nonparticipating" supplier under DMERC or vice versa.

You may need to reapply for a DMERC number if you have not submitted claims for four consecutive quarters. You must call and ask for a reapplication form.

If you do not have a DMERC number, call the National Supplier Clearing House at 866-238-9652 to obtain an application.

No surety bond is required at this time when filling out your application.

Part of your application process will be an unannounced on-site inspection.

Other requirements include the following:

You must have your hours of operation posted on your door.

You also need to have a complaint form available and a complaint resolution protocol established.

For other insurance carriers/HMOs/IPAs, make sure that you are designated as a DME supplier (beyond being a physician provider) and that their insured may be able to obtain these items from you. If you are not a designated supplier and if you dispense that DME item, you may not be reimbursed. Trying to collect for this item from the patient may be difficult and create ill-will towards your practice if they could have gotten this item covered at an outside/designated facility. If you are allowed to dispense DME items, make sure that you understand all of the carrier's rules, restrictions, and billing protocols.

Assignment

PARTICIPATING SUPPLIER accepts assignment on ALL cases. There is no "limiting charge" for any DME supplies. The supplier bills Medicare. Medicare will pay 80% of the allowable charge or the reasonable and customary fee (after deductible has been met). The supplier may collect the remaining 20% and any amount that went towards the deductible from the patient at the time of service (if the amount is known) or after payment is received from Medicare. It is advisable however to delay billing the patient until receipt of their payment determination to ensure that the allowed charges or remaining balance is accurately shown. A violation of the assignment agreement occurs if the physician collects (or attempts to collect) from the patient any amount, which when added to the benefit check exceeds the Medicare allowance. For non-covered services a "participating supplier" may collect at the time of service.

NONPARTICIPATING SUPPLIER under DMERC can elect on a case-by-case basis to accept assignment or not. If the supplier agrees to accept assignment, the above scenario applies. If the supplier does not accept assignment on a covered item, the payment may be collected from the patient—when the item is actually dispensed—not when initially ordered. A claim is submitted to Medicare and the insurance check would then be sent directly to the patient. For non-assigned claims you may bill your usual and customary fee. Medicare will still pay 80% of the allowable fee for that item (after deductible has been met) or 80% of billed charges, whichever is lower. <u>However, the patient is responsible for the balance in full not just the 20% of the allowable charges</u>.

As a designated supplier for Medicare, you may accept orders/prescriptions to dispense DME items from other physicians. In this capacity your relationship to the patient is only that of a supplier not a physician. You would bill the insurance company or the patient only for the item prescribed. You would not bill this as a professional consultation in addition to supplying the item unless the prescribing physician specifically requests a consult, and if all of the medical necessity and documentation requirements for a consultation (per CPT criteria) are met. Yet if you feel that the item requested is incorrect, it would be appropriate in the spirit of offering top-quality care to the patient to contact the prescribing physician and voice your concerns.

There is a question if a podiatrist/DME supplier could dispense other DME supplies such as splints and orthotics for other body parts, glucose strips, etc. This may depend on state requirements as well as individual plan provisions. This is a bit of a gray area and you should consult with an attorney who specializes in health care as well as your malpractice carrier before proceeding with dispensing "non-podiatric" DME items.

Fee Schedule

When an insurance company covers an item, you are held to their fee schedule and any policy/protocols listed in your contract with the insurance company. For example, certain services pertaining to the DME item such as casting, dispensement, or adjustments, patient training/education in the use of the item may be included in the fee allowance for the device, similar to the global fee concept with surgery.

For non-covered devices, you are not bound to any fee schedule and hence you may charge your usual and customary fee. It is recommended to have a single fee schedule for all of your services provided including DME whether they are covered or not.

You should also check with current and any new insurance carriers regarding their fee schedule. This is especially true for HMOs and capitated programs. You may find that their fee allowance is not acceptable to you. You should try to renegotiate your contract to a more acceptable allowance. Or, you may elect not to provide DME to that insurance company's insured. Make sure that this does not violate terms of your contract. You cannot bill the patient a "surcharge" to make the fee more acceptable.

If you are in a capitated program, you may consider "carving out" the DME portion out of your capitation fee if the DME fee reimbursement schedule is unacceptable. This way you can charge your usual and customary fee schedule for those "carve-out" items.

Communication

Whenever you speak with an insurance carrier, always record the date, time, and name of the person you spoke with. Be specific as possible and record what you were told. This information may be vital when formulating an appeal for denial of payment. Make sure that you ask the telephone representatives to check on any specific foot exclusions. An inexperienced telephone person may state that DME is a covered benefit as a general policy but they may not look deeper into the fine print and find that there may be certain exclusions. If they state that there are no exclusions, document this.

Office Forms/Policies

You should have a clear policy in your office with regard to DME items, especially orthoses. It is recommended to utilize preprinted forms describing the device, coverage issues or possible non-coverage, and other charges associated with the devices (i.e., casting fee, orthotics fees). That way there are no surprises and the patent is fully aware of any out-of-pocket costs.

You should also have a policy dealing with complaints that patients may have with the device and a protocol for resolution of complaints. Be prepared to address issues beyond the device itself. Patients may have concerns regarding the appearance of the device, fit in various shoes, etc. Specifically with dispensement of shoes, patients may have issues with the appearance, color, laces vs. Velcro, etc.

Billing Protocols

When billing for a DME item submit a CMS-1500 claim form using the appropriate Healthcare Common Procedure Coding System (HCPCS) code. If you are unsure of the proper code to submit, SADMERC (Statistical Analysis DMERC) at 877-735-1326 or write: Palmetto Government Benefit Administrator, P. O. Box 100143 Columbia, SC 29202-3143. Describe the item, model number (if any), manufacturer, and any other information you may have and they will see if there is an appropriate HCPCS "A" or "L" code.

Check with the involved carrier regarding billing for DME. Many carriers including Medicare will want you to bill for DME when the item is dispensed not when ordered or molds obtained. This is important if the insurance company gave you an authorization with a fixed time frame. If so, make sure that the item is molded, fabricated, and dispensed within that time frame.

When billing multiple separate items there is no need to add a –51 modifier to subsequent items. Each item is fully reimbursable at its allowable fee.

For orthoses or other bilateral devices some carriers may prefer you to use RT/LT modifiers. In this case bill each item line by line. Other carriers may prefer to bill single-line items but use the appropriate "units" when billing in box 24G of the CMS-1500 claim form.

Place of Service

The place of service should be shown on your claim form as the place where the item, equipment, or supply would be used. Since the item would be used at home, the proper place of service would be "home" or place of service "12" even if it was dispensed in your office. Medicare only pays for place of service "12" (home), "33" (custodial care facility—NOT SNF/NH), "54" (ICF/mental retardation), "55" (residential substance-abuse treatment facility), and "56" (psychiatric residential treatment center). Medicare will also pay for DMEPOS in place of service code "34" (hospice) as long as the item being billed is not for the primary diagnosis they are on hospice. DMERC does not cover DME to the supplier in place of service "31" (SNF) or "32" (nursing home). However they do cover prosthetics, orthotics, and related supplies and surgical dressings as part of the facility's services.

Obtaining a Proper Denial

Specifically for Medicare, orthoses are not covered unless they are part of a shoe which is attached to a brace. Since this service is not covered by statute, no Advanced Beneficiary Notice (ABN) is required. For non-Medicare patients you should generate an office form (similar to an ABN) that you have the patient sign indicating that the item is not covered by their plan and that they agree to pay for the device in full. Again this may help minimize any billing confusion later on.

The primary insurance may not cover a specific DME item but the secondary insurance carrier might. In this case you must bill the primary insurance carrier first to get the denial and then you may bill the secondary carrier. For Medicare, bill your DMERC carrier not the carrier that provides Medicare Part B services for you to get the proper DME denial.

To obtain the proper denial from Medicare for a non-covered DME item, append the HCPCS code with the GY modifier indicating that this item is not covered by statute. An incorrect denial message may adversely affect coverage by the secondary carrier. If the primary insurance carrier deems an item not medically necessary, so may the secondary carrier. But if the denial reads not a covered service, then the secondary carrier would implement its coverage criteria and determine if payment is allowed under its plan.

Medicare does not require claims to be submitted for any **non-covered** item or service that is excluded from coverage by Medicare statute. The exception to this is if the patient requests a claim to be submitted if he or she believes the item may be covered or to obtain a formal Medicare determination. It is a patient's/beneficiary's right to such a determination. In this instance, bill the item with a **–GA, –GZ** modifier indicating that a potentially non-covered item or service was billed for denial or at the patient's request.

Other carriers may require that all claims be submitted for adjudication whether the service is covered or not.

Incorrect/Overpayment

If you know that the item was paid for incorrectly, the monies should be returned to the carrier. If the determination is based upon "medical necessity" and hence you cannot know if it may be paid or not, then you may deposit the monies. If the insurance company comes back at a later time and wants a refund, you do have legal rights. If you acted in good faith, called the carrier (and it is documented), and submitted a proper claim for a medical necessary and reasonable item, then you may not have to return such monies. There are state laws protecting providers from such refund demands. Check with an attorney or your state association for state laws in this regard.

Modifier

- **GA modifier**: Add this modifier when billing for a Medicare item or service that the provider feels (1) may be deemed a not medically necessary service, (2) the patient has been informed of such and given the specific reason why the doctor feels it may be deemed medically not necessary, and (3) that an ABN is on file.
- **GZ modifier**: It is similar to the −GA modifier except that it is used when an ABN is not on file.
- **GY modifier**: This modifier indicates that the supply is not a covered benefit of Medicare and that a denial is required such that a secondary insurance company may be billed.
- **KX modifier**: Some items have specific Medicare policies and requirements for coverage. This indicates that certain specific requirements found in the documentation policy have been met and evidence of this is available in the supplier's record such as documenting diabetes with PVD or ulcer history to validate the necessity for a therapeutic shoe.
- **NU modifier**: Certain items require this modifier (especially for Medicare DMERC) if the item was dispensed as new item.
- **RR modifier**: Certain items require this modifier (especially for Medicare DMERC) if the item was rented.
- **UE modifier**: Certain items require this modifier (especially for Medicare DMERC) if the item was dispensed as used.

Deductibles/Deposits

For covered DME items, you may or may not be allowed to collect a deposit. Make sure that collecting a deposit does not violate your contract with the carrier.

For most carriers you are allowed to collect any co-pay or unmet deductible portion at the time the device is dispensed.

For non-covered items you can collect the entire fee up front at the time of ordering the item or obtaining the mold. It is recommended to at least obtain a deposit, which covers the hard cost of the DME item, before proceeding with fabrication of the item. This way if the patient changes his or her mind or does not return to pick up the device at least you will cover the lab fees.

Sales Tax

With any DME item dispensed from your office, check with your state regarding requirements for collecting sales tax. Medicare does not pay for sales tax separately. State laws may vary as to what is considered a "medical device." In some states, shoes (including "diabetic shoes") may have a separate classification when it comes to medical devices and may be subject to sales even though other medical devices are not.

Dispensing Requirements

You should have the patient sign a form indicating that he or she received the DME item (the item should be itemized as to device and any associated additions/ modifications to the device), the device fit well, and patient instructions were reviewed. The HCPCS codes, description of the device, and associated items/ additions should be listed as well. For Medicare patients, you should also dispense the 21-point Supplier Standards. You do not have to indicate the specific costs and charges billed to the carrier.

Patient Education

Dispensing the orthotic and associated patient education is generally including the fee allowance for the orthotics itself. CPT codes 97760-62 are for orthotists not physicians.

Replacement Interval

The term Durable Medical Equipment implies that the item, as the name implies, is durable and should last for some time. This time interval may vary between carriers. This may range from 1 to 5 years for certain DME items. Items can break or wear out prematurely, or the patient's condition, and therefore their prescription, may change as well. You need to be aware of each carrier's policies on this and potential appeal processes to obtain replacement DME items for your patient. Documentation is very important in this regard. Be very clear how and why the item broke or wore down and what are the changes in the patient's status that warrant a new device earlier than expected.

Especially with orthoses, multiple pairs are often necessary to accommodate various styles of shoes. You should be aware of each carrier's rules regarding multiple DME items. A patient may be involved in different work duties at their job, which requires different shoe gear. Contrast this with a patient wanting several pairs for personal preference. Many athletes may have a locker at a gym and want to leave a pair there or in their gym bag for convenience. Many orthotic labs keep molds on file for many years. You should consider developing a formal office policy on obtaining multiple pairs of orthotics when multiple pairs are not covered by the insurance plan.

Inability to Deliver DME

If a custom-made device was fabricated but not dispensed to the patient because the patient died, no longer needed it, etc., payment can be made based upon the supply cost of the item. Use the date the patient died or order cancelled as the date of service. Indicate such on the claim form. It is recommended to submit this as a paper claim with an explanation attached.

Specific Items

Orthoses

There are two categories of orthoses: prefabricated insoles or custom foot orthoses. Most insurance companies will not pay for prefabricated insoles even when dispensed in your office. They may sometimes pay (incorrectly?) for them as a supply code 99070. Generally, prefabricated insoles are a CASH item.

Custom Foot Orthoses

Most insurance companies have policies regarding custom foot orthoses. Medicare does not allow coverage for orthoses unless they are dispensed as part of shoe, which has a brace attached. Many insurances follow that guideline as well. There may be separate allowance for diabetic orthoses when dispensed as part of the diabetic shoe program, which will be discussed later.

The fabrication of an orthotic device includes many components. First there is the determination as to whether an orthotic device is an appropriate treatment option or not for the patient's presenting problem. This is an evaluation and management service (E/M). As with any E/M service, document your history, and examination and decision making, and select the most appropriate E/M code level *based upon your documentation in the chart not the eventual diagnosis*. Insurances will also use this documentation to determine medical necessity per its guidelines.

Use of, or prior history of use of, prefabricated insoles or good results with a foot strapping (as a diagnostic or therapeutic tool) may also help validate the medical necessity of formal orthotic devices.

Medicare does not cover foot orthotic devices by statute. The orthotic device and all services directly related to the molding, fabrication prescription writing, dispensement, and adjustments are not payable either. Other insurances may follow this same protocol. Some may allow portions of the orthoses and its related services paid.

If the patient presents in your office, the decisions are made to proceed with custom orthotic devices, and the mold is obtained, the E/M service should be payable. The orthoses and related services may or may not be.

If the athlete is rescheduled to return to the office at a later date for casting or biomechanical evaluation, then there is no separately identifiable E/M service, which should be billed on that day. The examination has been performed and the decision has been previously made to proceed with an orthosis.

Orthosis Casting

There is no specific CPT code for casting for orthotic devices. Check with the specific carrier what their policy is and what they will allow.

The recommended code to use is CPT 29799, the unlisted casting procedure code. This code is billed once for obtaining molds for a pair of orthoses. This code also includes the plaster, foam block, or other casting materials. Do not use HCPCS codes A4580 and A4590 as this implies the use of an entire roll of plaster material. Insurance companies may recognize CPT 29799 code for separate payment or the casting component may be included in the overall fee allowance for the orthotic device.

The use of CPT 29515 is also not appropriate as this is a code for applying a posterior splint not casting for an orthotic device.

HCPCS code S0395 is another option. The description of this code is "impression casting of a foot performed by a practitioner other than the manufacturer of the orthotic." This would seem to fit perfectly when a doctor takes the mold and then ships off the mold to be fabricated by an outside lab. Many carriers do not accept HCPCS codes however.

The use of machines which scan the foot and generate a "mold" may or may not be payable separately. Billing a CPT code implies that a professional service was performed. Is there a professional service preformed having the patient stand on a machine? Was the foot held in corrected position, midtarsal joint locked, first ray plantarflexed, etc. Check with each insurance carrier to determine their policy on foot scanning machines.

Biomechanical Examination

Commonly performed tests as part of an orthosis workup include the manual muscle testing and the range-of-motion examination. **CPT code 95831 is described as muscle, testing manual with report, extremity.** Therefore a complete testing of each muscle in that extremity needs to be performed and recorded and formal interpretation/report must be generated. Simply stating "muscle-testing WNL" is not acceptable. The next component is if such a test is medically necessary and reasonable. Does the patient have a myopathy or muscular dystrophy, which requires a complete extremity exam vs. healthy runner with arch strain? Just performing the test does not mean that it should/will be paid.

The next test commonly billed is **CPT 95851 range-of-motion measurements and report each extremity.** Again this implies that all joints in the extremity are tested, measured, and recorded and an interpretation/report generated. You must also document the medical necessity and reasonableness of doing this examination. Listing WNL is not appropriate. Is checking the hip and knee range of motion medically necessary to create an orthotic for hallux limitus? Document why each test is required.

When medically necessary and reasonable CPT 98531 and 95851 should be billed as 95831-RT and 95831-LT and CPT 98551-RT and 95831-LT.

Gait Analysis

Gait analysis should generally be included as part of your E/M workup on the patient.

Do not use CPT code ranges 96000–96004. The introduction section of this code series in the CPT book specifically states that these codes are to be used when the gait analysis is performed in a designated motion analysis laboratory utilizing true 3D analysis, multiple video cameras, etc. Watching the patient walk back and forth in your hallway or videotaping alone does not qualify for this code series. Patients which generally qualify for this type of examination are those with neuromuscular gait abnormalities, muscular dystrophy, etc. When purchasing gait analysis machines make sure that you check with your principal insurance companies to make sure that they will pay on the use of that machine/code or you may spend a lot of money with no revenue source.

Patient Education

Dispensing the orthoses and associated patient education are generally including the fee allowance for the orthoses. CPT codes 97760–62 are for orthotists not physicians.

Orthoses HCPCS Codes

There are several types of custom orthotic devices.

L3000: These are listed in orthoses and prosthetic manuals as UCBL devices (Fig. 35.1). The description indicates a device molded to a patient model and shows a device with a heel cup and heel support/stabilization with a post. This most closely resembles the classic custom foot orthoses.

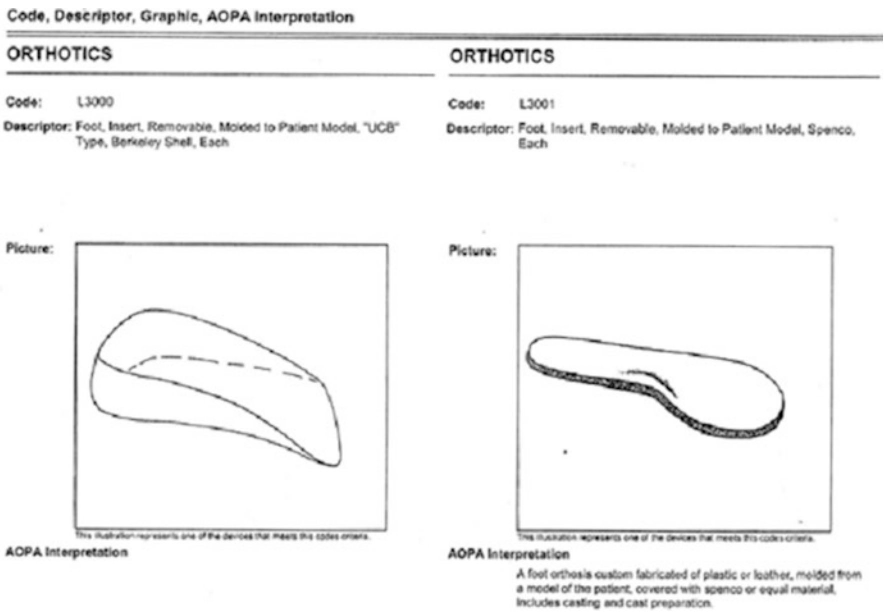


Fig. 35.1 L3000

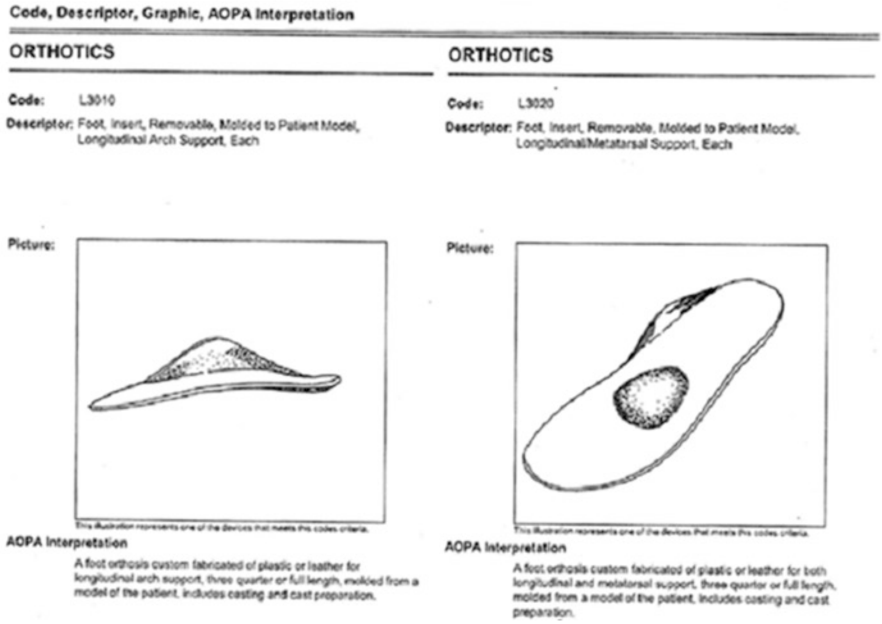
L3020: This device is also molded to a patient model but does not have a heel cup nor is it posted (Fig. 35.2).

L3030: This is a device molded directly to a patient's foot (Fig. 35.3). Therefore if a cast is not made of the foot, clearly this is not an appropriate selection.

Orthosis Modifications

There are various HCPCS codes for orthosis repairs in the code range L4205–4210. Most orthotic companies will offer some type of guarantee for their products for premature breakage or incorrect prescription, As far as repairs, many insurance carriers do not pay for such services. Adjustments to the orthoses such as modifying the post, adding modifying forefoot extensions, and grinding down a rough area may not be payable separately. You could charge the patient directly for these repairs.

Sending orthoses back for minor repairs can be expensive and time consuming, plus the patient does not have the device. As a practice management tool, being able to perform minor repairs may be a great practice builder. Patients like the efficiency of having you repair the device promptly vs. a week or more wait if the orthosis is sent back to the orthotics lab. During this time the patient is without the use and benefit of the orthotic device. Plus this allows you an opportunity to review the orthosis and consider additional changes/modifications; see if the patient would benefit from a second pair of orthoses or possibly attempt other non-orthosis-related treatments, i.e., physical therapy for some residual pains.



Code, Descriptor, Graphic, AOPA Interpretation

ORTHOTICS

Code: L3010

Descriptor: Foot, Insert, Removable, Molded to Patient Model, Longitudinal Arch Support, Each

Picture:

This illustration represents one of the devices that meets this codes criteria.

AOPA Interpretation

A foot orthosis custom fabricated of plastic or leather for longitudinal arch support, three quarter or full length, molded from a model of the patient, includes casting and cast preparation.

ORTHOTICS

Code: L3020

Descriptor: Foot, Insert, Removable, Molded to Patient Model, Longitudinal/Metatarsal Support, Each

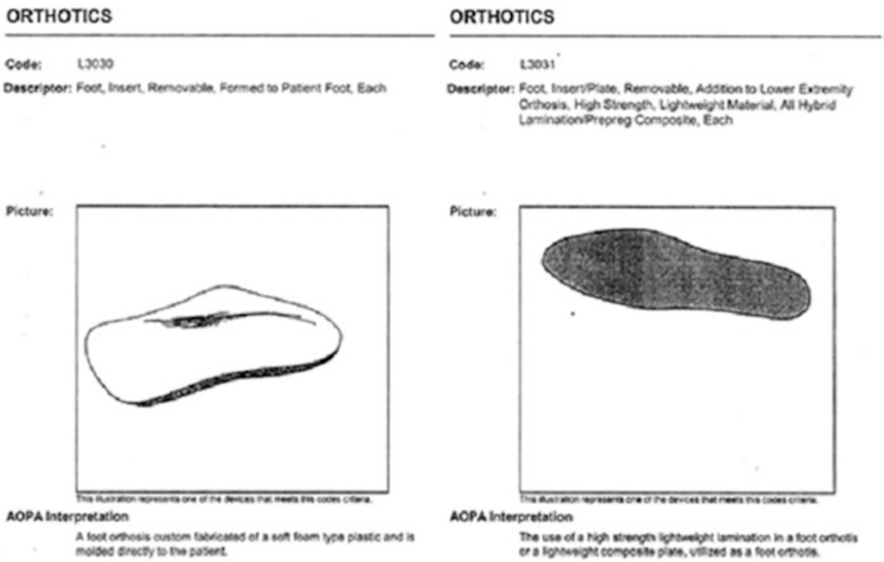
Picture:

This illustration represents one of the devices that meets this codes criteria.

AOPA Interpretation

A foot orthosis custom fabricated of plastic or leather for both longitudinal and metatarsal support, three quarter or full length, molded from a model of the patient, includes casting and cast preparation.

Fig. 35.2 L3020



ORTHOTICS

Code: L3030

Descriptor: Foot, Insert, Removable, Formed to Patient Foot, Each

Picture:

This illustration represents one of the devices that meets this codes criteria.

AOPA Interpretation

A foot orthosis custom fabricated of a soft foam type plastic and is molded directly to the patient.

ORTHOTICS

Code: L3031

Descriptor: Foot, Insert/Plate, Removable, Addition to Lower Extremity Orthosis, High Strength, Lightweight Material, All Hybrid Lamination/Prepreg Composite, Each

Picture:

This illustration represents one of the devices that meets this codes criteria.

AOPA Interpretation

The use of a high strength lightweight lamination in a foot orthotis or a lightweight composite plate, utilized as a foot orthotis.

Fig. 35.3 L3030

There are several modifications that can be made to orthoses and shoes listed in HCPCS code range L3300–3649 and for AFO type devices HCPS codes L1900–2999. Again, these may or may not be payable. Clearly document why modifications need to be made.

E/M Services with Regard to Orthosis Management

Be clear in your chart; note the basis for the office encounter. If the patient came in solely to have the orthosis adjusted because there was a sharp edge or it was a bit too long and irritating the patient, some insurance may not pay for this as it may be deemed included within the orthosis fee allowance. No office visit may be allowed in that regard as there is no E/M service performed. Contrast this with the patient returning for evaluation of their plantar fasciitis, which is improving, but reached a plateau. In the latter case the E/M service would be allowed as you are addressing the plantar fasciitis, possibly changing treatment algorithm and/or adjusted the orthosis or post the device to try to increase the control of the orthosis to make it more effective.

Therapeutic Shoes for Diabetics

Custom-molded shoes or extra-depth shoes with custom inserts are covered for qualifying diabetics.

Coverage per *calendar* year:

- One pair of custom shoes and two additional pairs of inserts (excluding the one pair that came with the shoe), or
- One pair of extra-depth shoes and three pairs of inserts (excluding the pair that came with the shoes). A depth shoe definition is one that allows for a 3/16 insole leather and has a form of closure (laces or Velcro). It must be available in full and half sizes and in at least three widths.
- Substitutions: One may substitute a pair of inserts for rocker bottom soles, metatarsal bars, wedges, offset heels, flared heels, or Velcro closures. This is not an exhaustive list rather the most common shoe modifications.
- Extra insoles can be covered pending verification in writing.

Certification:

- A M.D. or D.O. who is responsible for treating the patient's diabetes must certify the need for diabetic shoes. (A podiatrist or orthopedist cannot certify.)
- A podiatrist may prescribe and furnish diabetic shoes.

Coverage Criteria:
There must be documentation in the chart of one or more of the following conditions to warrant coverage under this program:

- Peripheral neuropathy with evidence of callus formation
- History of pre-ulcerative calluses
- History of previous ulceration
- Foot deformity
- Previous amputation of the foot or part of the foot
- Poor circulation

Payment:
Payment is limited to 80% of the reasonable charge up to a limited amount. If the sole purpose of the visit is to fit or dispense the shoes, no office visit is payable separately. Starting in 2005, the fee schedule will change for reimbursement and fall under the DME fee schedule.

Misc:
If the patient has a leg amputation, still bill for one pair of shoes but only for one (side) insole. Otherwise dispense and bill for the three insoles at the time the shoes are dispensed.

Codes:
Custom shoe A5501 (diabetic)
Depth shoe A5500 (diabetic)
Prefab insoles (not heat molded) A5510 (diabetic)
Prefab insoles (heat molded) A 5512 (diabetic)
Custom-molded insoles A5513 (diabetic)
Longitudinal insoles with arch and filler for amputated portion foot L5000

NOTE: The above codes apply to diabetics in need of a protective shoe with various insole choices. A diabetic who does not meet the above criteria and who may need a "standard" orthosis (i.e. L3000–L3030 for plantar fasciitis) would not qualify for coverage under this program.

Cam Walker/Braces

The definition of a brace is a rigid or semirigid device used for the purpose of

- Supporting weak or deformed body member or restricting or eliminating motion in diseased or injured part of body
- Must provide support and a counterforce on a limb or body part that it is being used to brace

Some of the more common HCPCS codes for AFOs include:

- AFOs, codes
- L1900, L1902-L1990, L2106–L2116, L4350, **L4360, L4386**, and L4631
- KAFOs, codes
- L2000–L2038, L2126–L2136, and L4370

Coverage for these devices varies depending on if the patient is ambulatory or not and if the device is a custom-fabricated device or a prefabricated device. As always, documentation is important. Some basic points to document are whether the patient is ambulatory or nonambulatory and why there is a need for a custom-fabricated vs. a prefabricated device.

There needs to be a detailed written order in your chart. If you are sending the patient out to an orthotist, a separate RX would be required. Depending on your DME carrier, if you are both prescribing and dispensing the device the written order can be part of your chart note. Some may still require a separate order. Regardless the following information needs to be listed on the RX or within your chart note:

- Provide the product that is specified by the ordering physician
- Type of orthosis dispensed
- Written order
- Proof of delivery
- Medical records
  - Documentation of the patient's condition
  - Documentation to support the medical necessity of a custom vs. prefabricated device
  - Why a prefabricated device would not meet the patient's needs
  - Method of fitting and/or fabrication (OTS or custom fitted
- Beneficiary Documentation or ABN
- Use the code that most accurately reflects both the type of orthosis and the appropriate level of fitting

Ambulatory vs. Nonambulatory Patients

Ambulatory Patients

AFO/KFO items are covered for AMBULATORY patients when the patient is:

- Ambulatory (or plan to move to an ambulatory status must be documented in medical record)

This is an important point. There has been an issue in the past with some Medicare DME carriers where cam walkers were being denied if the patient was non-weight bearing even for a short period of time. CMS interpreted this temporary non-weight-bearing status to mean that the patient was nonambulatory and hence the device would not be covered. Therefore make sure that your chart states that the patient will be transitioning to a weight-bearing status.

- Weakness or deformity of the foot and ankle
- Require stabilization for medical reasons
- Have the potential to benefit functionally

For KAFOs, the requirements include:

- Beneficiaries who meet coverage for an AFO
- Require additional knee stability

A ***custom-fabricated*** device is covered for ambulatory patients when **one** of the following criteria is met/documented in the medical record:

1. Beneficiary could not be fit with prefabricated AFO, **or**
2. Condition necessitating orthosis expected to be permanent or of long-standing duration, **or**
3. Need to control the knee, ankle, or foot ***in more than one plane***, **or**
4. Documented neurological, circulatory, or orthopedic status that requires custom fabricating over a model to prevent tissue injury, **or**
5. Healing fracture which lacks normal anatomical integrity or anthropometric proportions

Nonambulatory Patients

For nonambulatory patients L4396 or L4397 is covered when a beneficiary is non-ambulatory or minimally ambulatory and if all criteria 1–4 **or** criterion 5 is met:

1. Plantar flexion contracture of ankle (Dx 718.47) with dorsiflexion on PROM testing of at least 10° (i.e., non-fixed contracture); **and**
2. Reasonable expectation of ability to correct contracture; **and**
3. Contracture is interfering or expected to interfere significantly with beneficiaries' functional abilities; **and**
4. Used as component of therapy program which includes active stretching of involved muscles and/or tendons; **or**
5. Beneficiary has plantar fasciitis (Dx 728.71). Code L4398 is also used for an ankle-foot orthosis which is worn when a beneficiary is nonambulatory.

For nonambulatory patient custom orthotic coverage is less clear. Documentation is the key here. Make sure that you document why a nonambulatory patient requires a custom device. "Preventative" needs such as preventing a contracture may not be enough to warrant coverage.

Custom-Fabricated vs. Off-the-Shelf Devices

Custom-fabricated orthotics are:

- Items that are uniquely made for an individual beneficiary. No other beneficiary would be able to use the specific item.
- Items that are individually made from basic raw materials including, but not limited to, plastic, metal, leather, or cloth in the form of unshaped sheets, bars, or other basic forms and involve substantial work such as vacuum forming, cutting, bending, molding, sewing, drilling, and finishing prior to fitting on the beneficiary.
- Items must be individually fabricated over a positive mold of the beneficiary. A positive model may be created using various methods, e.g., traditional casting methodologies or using CAD/CAM or similar technology (not all-inclusive list). In all cases in order to be considered a custom fabricated, the item must be created over actual physical mold of the body part.
- Items that require the expertise of a qualified practitioner to custom fabricate.

Off-the-Shelf Devices

These types of devices may be prefabricated or custom fitted.

Prefabricated Off-the-Shelf Devices:

- May or may not be supplied as a kit.
- Requires minimal self-adjustment upon delivery; this refers to adjustments made when you first dispense the device not on follow-up examinations.
- Does not require expert fitting rather—this can be done by a beneficiary, caretaker, or supplier.

Custom-Fitted Off-the-Shelf Devices:

- May or may not be supplied as a kit.
- Requires substantial modification upon delivery: this refers to adjustments made when you first dispense the device not on follow-up examinations.
- Requires expert fitting by a physician, certified orthotist, or someone with specialized training.

NOTE: The definition of minimal vs. substantial modifications of a device is somewhat unclear. Adding additional padding to protect a bony prominence or adding a heel lift or wedge would not be considered substantial. Documentation here is key to list what adjustments were made to the device and why these adjustments had to be made by a fitting expert.

Some examples of common custom-fitted vs. off-the-shelf codes:

Custom fitted		Off-the-shelf
L4360	→	L4361
L4386	→	L4387
L4396	→	L4397

Currently both custom-fitted and off-the-shelf devices are reimbursed at the same. This could change in the future.

For the classic cam walker that we would dispense for a fracture, the off-the-shelf codes would be the most correct.

For items without a designated HCPCS code, e.g., L2999, you must include a narrative description of the item or manufacturer's name and model name/number. The suggested manufacturer suggested retail prices and for replacement components the HCPCS code or manufacturer name and model number of base orthotic.

Non-payable Services

Time involved with:

- Evaluating the beneficiary for the brace (services to evaluate and treat the patient's condition are separately payable per medical necessity).
- Taking measurements, making a cast, making a model, use of CAD/CAM.
- Making modifications to a prefabricated item to fit it to the individual beneficiary.
- Follow-up visits specifically for the brace (services to evaluate and treat the patient's condition are separately payable per medical necessity).
- Making adjustments at the time of, or within 90 days of, the delivery.
- Use of additional codes L4002–L4130, L4392.

Repairing Orthotic Devices

- Covered when necessary to make orthosis functional.
  - Must have supporting documentation of reason for repair.
- If expense for repairs exceeds estimated expense of providing another entire orthosis, no payment will be made for amount in excess.
- Not covered if item was previously denied.
- New order not required for repairs.

L4205

- Repair of orthotic device, labor component, per 15 min.
- Include narrative on claim explaining what was repaired.

– Can only bill for time involved in actual repair or for medically necessary adjustments made more than 90 days after delivery.
– Cannot use to bill for time involved in other professional services.

L4210

- Repair of orthotic device, repair or replace minor parts.
- Include narrative on claim describing each item billed. Replacement of complete orthosis or component of orthosis is covered if due to:
  – Lost, stolen, irreparable accidental damage.
- RA modifier required.
  – Significant change in beneficiary's condition.
- New order required for any replacement.
- Supplier's record must document reason for any replacement.
- Replacement components provided on a routine basis, without regard to whether the original item is worn out, are not covered.
- The padding/lining of an AFO can be replaced if reasonable and necessary.

Post-Op/Wooden Shoes/Cast Shoes

Medicare does not cover these under any circumstances. They are therefore billable to the patient directly. An ABN is not required since this item is never covered. There is no limiting charge. The appropriate L-code for this shoe is L3260. The denial will read—not a covered service. This would therefore allow you to bill a secondary carrier. Non-Medicare payors may or may not cover these items as a separate item.

Items/Supplies Dispensed from the Office

Some items are covered, many are not. Many are included in the surgical fee allowance.

Covered items include:
Removable ankle brace
"Cam" walkers: nonpneumatic
Fixed AFO
Ritchie brace with or without drop foot hinge
Arizona (gauntlet)
Take-home supplies for wound care such as Duoderm, hydrogels, and Polymem. They are not covered when you use them in the office.
Night Splints

Crutches E0110–0117
Walker E0130–0147
Canes E0100–0105

Non-covered items include:
Ace bandage, in-office bandages, gauze, Coban, roll gauze dispensed to patient not covered above. OTC splints, prefabricated insoles, pads, heel cups, tape, and other commercial-type products, prescription medicines dispensed in the office such as pain pills, antibiotics, antifungal preparations, topical steroids, etc.

These are billable to the patient, with no ABN and no limiting charge.

Strapping

This procedure is payable when medically necessary and reasonable. The supplies are included in the allowance for the procedures. For Medicare, strappings are not paid when performed on the same day as an injection.

BK/AK Casts

Application of a BK or AK cast is payable per medical necessity. The supplies are paid in addition to the cast application CPT code. Bill HCPCS code A4580 for plaster supplies and A4590 for synthetic supplies bill for each roll applied by listing that number of rolls used in box 24 G as units #X.

For Medicare use the appropriate Q code for cast supplies. Bill this as unit 1 not per roll. Other supplies such as stockinet and under padding are not payable separately.

Many insurance companies will not pay for cast shoes, so these would be billed as a cash item directly to the patient.

Billing Scenario

1. New patient, 25-year-old runner presents with AM pain in the right heel after increasing his mileage for the past few months. Pain is a 6 on a scale of 1–10. He denies any specific trauma. Pain is described as a dull ache in his heel. It is especially worse in the morning or after he has been off of his foot for >30 min. He has tried ice and ibuprofen without any improvement. He may have had a similar set of symptoms a few years ago but those responded quickly with rest, ibuprofen, and buying better running shoes.

   His past medical history is unremarkable. He takes OTC allergy medication PRN seasonal allergies. He denies any drug allergies. There is a history of rheumatoid arthritis in the family.

Vascular: 3+/4 DP and PT pulses B/L. There's no clubbing or cyanosis of the digits. There is no pedal edema.

Neurologic: DTR are 2+/4 B/L; there is no sensory loss noted in the foot; there is no Tinel's sign with percussion of the PT nerve.

Dermatological: Good skin temperature, texture, and tone. There is mild contusion on the right hallux nail but no infection noted.

Musculoskeletal: Tenderness is along the course of the right plantar fascia. There is no pain on the left side. There is maximum pain at the insertion point of the fascia into the heel. There is no edema, erythema, or ecchymosis. There is no ankle, STJ, or MTJ pain with ROM. There is no crepitus. He has a very flexible midfoot. There is good muscle strength in all four-muscle groups B/L. He has a mild HAV but that is asymptomatic.

Assessment: Plantar fasciitis right foot.

Plan: Reviewed etiology and treatment options for plantar fasciitis.

Obtained X-ray (two views), which did not reveal any spur formation. There were no fractures. Bone stock was normal, no degenerative joint disease noted.

Injected plantar fascia at the heel insertion area with 1% xylocaine plain mixed with 0.5% bupivacaine plain and 1 cc triamcinolone acetate. 10. Reviewed possible steroid flare.

To continue with ice TID for 15 min and rest

Sample Billing:
CPT 99203
CPT 73620-RT
CPT 20550

J3301 (steroid only, local anesthetic not payable nor is syringe, needle, etc.)
[Notes: 99203 appropriate level of service based upon documentation, no need for contralateral X-rays since symptoms localized to the right heel and evaluation of the left heel would more than likely not affect the treatment plan for the right]

2. F/U patient doing better. Good initial relief but benefits waned as the week went on. No change in activities. Physical exam unchanged. Pains continue to be at the insertion point of the fascia. Suggest repeat injection with 1% xylocaine plain and 0.5% bupivacaine plain and triamcinolone acetate 10

   Sample Billing:
   CPT 20550
   J3301

   [No significant or separately identifiable E/M service rendered on this day, as H&P was more of an update with no new findings]

3. Patient still only 25% better. Pains the same. He mentions that his brother was recently diagnosed with some "different type" of arthritis. He notices that he is

limping more on the right. No change in physical exam except that he is walking with the right foot held more abducted. Still fascia insertional pain. Some medial foot pain noted as well especially at the navicular bone. Posterior tibial tendon strong and intact. Will apply a strapping to stabilize the arch and order arthritis panel blood tests

Sample Billing:
CPT 99212-25
CPT 29540

[This evaluation required additional workup and change in treatment plan, hence E/M payable in addition to procedure]

4. Patient still not any better overall and in fact it may be worsening although the strapping did temporarily seem to make the foot feel more secure. He did spend 3 h at a local mall last Sunday. Now there is more of a tearing-type sensation in the arch. Blood tests taken at the last visit are normal. Still localized pain at the fascia insertion point into the calcaneus. He is much more sensitive today to direct palpation of the plantar medial tubercle of the calcaneus. There is no sensory loss or Tinel's sign noted. Will order MRI to evaluate fascia for partial tear or even stress fracture in bone. With his flexible midfoot will schedule for bio-evaluation and orthosis fabrication. Orthoses are not covered by his insurance carrier. Patient understands this and wishes to proceed with the orthoses anyway. Orthosis payment form dispensed.

   Sample Billing:
   CPT 99213
   [Additional workup required and decision making to alter treatment course, obtain additional testing, etc.]

5. Bio Eval performed including muscle testing, ROM examination. See attached bio-evaluation form. Patient casted for orthoses, plaster molds obtained.

   Sample Billing:
   CASH $400 for orthoses and associated non-covered services [per insurance company guidelines. If this would be covered suggest obtaining prior authorization for orthoses and associated biomechanical testing. Obtain insurance company's preferred CPT code casting for orthotics as there is no specific CPT code for casting. If covered bill L3000-RT and L3000-LT for the orthoses]

6. Office called patient and informed them that orthoses have arrived, appointment made. Also informed patient that MRI did not indicate any obvious bone pathology and there is only mild thickening of the fascia consistent with plantar fasciitis. Adjacent ankle ligaments and tendons normal
   [Document any conversation with patients, not billable to insurance]

7. Office staff dispensed device and instructed in break-in process. No pressure areas noted by patient. They fit well in the shoes.

   Sample Billing:
   Possibly CPT 99211 as there was no encounter with the doctor. Some insurance companies may lump the dispensement and fitting of the orthotic in the cost of the device and not payable separately.

8. Patient came complaining that front edge binds under first met head. There was a ridge in the distal edge of the orthosis and this was reduced. Patient noted good relief.

   Sample Billing:
   Not billable to insurance as no patient evaluation performed per se. Any orthosis-related services may not be reimbursable separately. For those insurance companies that do not cover orthoses, any orthosis-related service would also not be covered. If the carrier covers the device, such minor adjustments would more than likely be considered included in the allowance for the orthoses. Unless otherwise stated in your insurance company contract you could bill the patient directly/cash for the orthosis adjustment.

9. F/U on plantar heel pain. Patient states that he is 40% better. He noticed good initial relief when he started wearing the device but then the improvement has leveled off. Symptom quality and location unchanged, just decreased pain level. Patient walks with less of a limp. There is less tenderness with palpation of the heel area. Suggest one additional injection of 1% xylocaine plain mixed with 0.5% bupivacaine plain and 1 cc triamcinolone acetate now that he has good biomechanical support. To continue ice, stretching, and 600 mg ibuprofen BID-TID PRN. Will augment his home stretching program with in-office physical therapy. Will perform ultrasound and icing three times per week for 3 weeks.

   Sample Billing:
   CPT 99212-25
   CPT 20550
   J3301

   [E/M payable as there is a more involved evaluation, including additional treatment options]

10. Patient presents for physical therapy. Ultrasound performed for 10 min on the plantar aspect of the right heel and along the entire course of the plantar fascia. Icing applied after ultrasound.

    Sample Billing:
    CPT 97035

[Ultrasound based upon 15-min increments, ice packs not payable as that is a modality that the patient can do themselves at home.]
—Six total physical therapy visits performed and documented—

11. At the seventh PT visit patient states he is still at the 40% improvement level, the injection and physical therapy did not offer any additional benefit. He is becoming more frustrated and his boss seems to be getting less sympathetic with him and his lower productivity at work. Physical exam unchanged with continued calcaneal insertional pain. No neurologic loss. Slight limp still noted in gait. Will stop physical therapy and cast the patient to rest his foot (BK synthetic cast). Even though he has stopped running he still walks and stands at least 5 h at work.

    Sample Billing:
    CPT 99212-25
    CPT 29425
    A4590 X 4 rolls

12. Three weeks later patient is no better. Reviewed etiology of plantar fasciitis. Reviewed treatment options common for this condition. Reasonable conservative treatment course completed and only remaining option at this point is surgical intervention if symptoms warrant. Reviewed ESWT, EPF, and the open procedure. Reviewed risks, benefits, and complications for each surgical procedure. Reviewed success rates with each option. Reviewed recovery times and anesthetic choices. Total time spent with patients 45 min.

    Sample Billing:
    CPT 99214

    [This is based upon documented face-to-face time spent with the patient in consultation. At this visit no significant history was obtained, and any exam was cursory. The bulk of the encounter was in consultation]

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