Evolution of Foot Orthoses in Sports

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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].

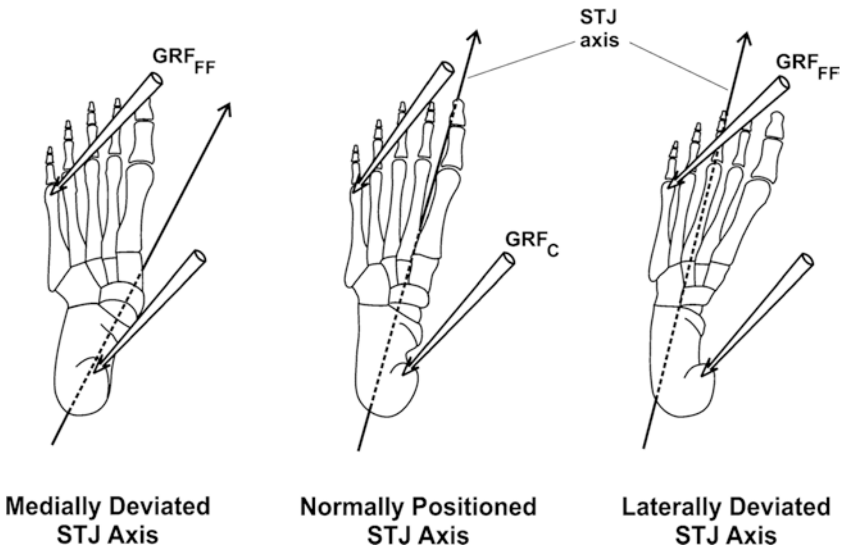

Fig. 2.1 In a foot with a normally positioned subtalar joint (STJ) axis (*center*), the ground reaction force plantar to the calcaneus (GRF_C), will cause a STJ supination moment since it acts medial to the STJ axis. Ground reaction force acting plantar to the fifth metatarsal head (GRF_{FF}) will cause 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

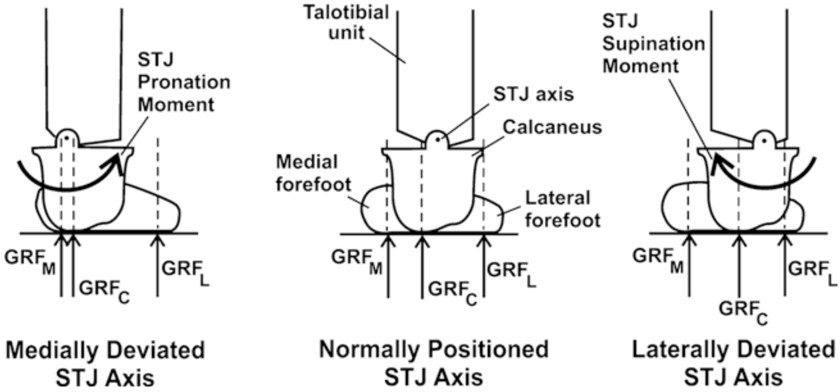

Fig. 2.2 In the model above, a posterior view of the right foot and ankle are modeled as consisting of the talus and tibia combined together to form the talotibial unit which articulates with the foot at the subtalar joint (STJ) axis. The external forces acting on the foot include ground reaction force (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

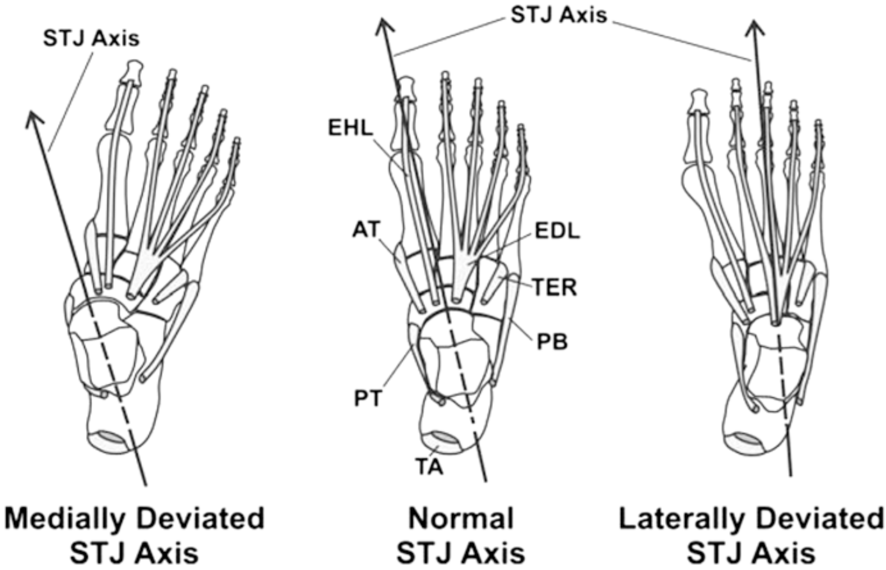

Fig. 2.3 In a foot with a normal STJ axis location (*center*), the posterior tibial (PT), anterior tibial (AT), extensor hallucis longus (EHL), and Achilles tendons (TA) will all cause a STJ supination moment when they exert tensile force on their osseous insertion points since they all insert medial 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].

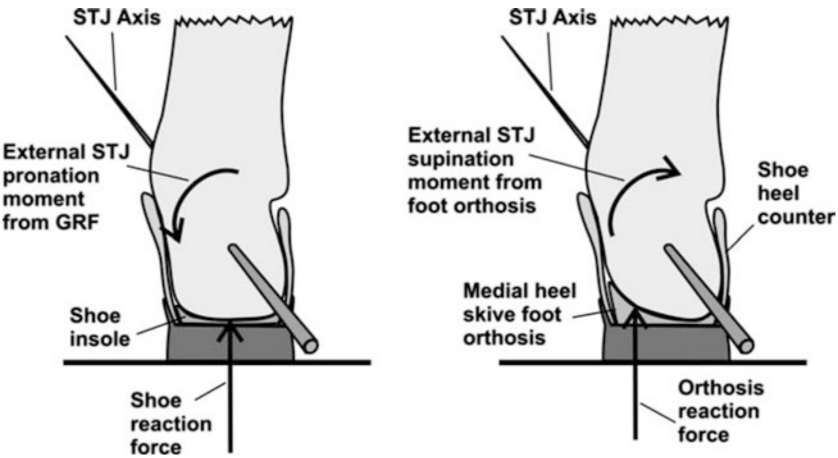

Fig. 2.4 In the illustrations above, the posterior aspect of the right foot with a medially deviated subtalar joint (STJ) axis is shown in a shoe without an orthosis (*left*) and also is shown in a shoe with a medial heel skive foot orthosis (*right*). In the shoe with only the insole under the foot (*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].

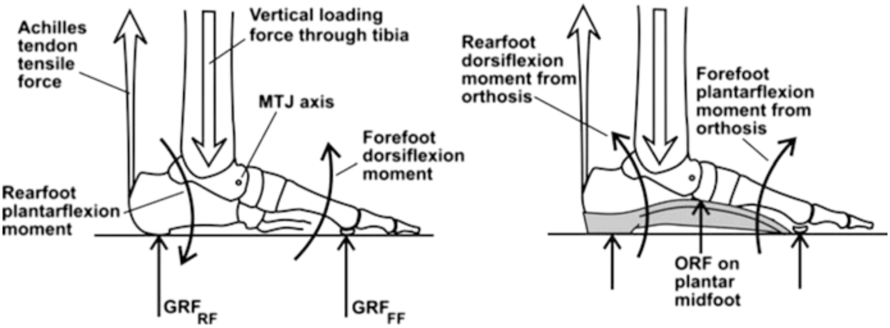

Fig. 2.5 During standing without a foot orthosis (*left*), ground reaction force acting plantar to the rearfoot (GRF_{RF}), Achilles tendon tensile force acting on the posterior rearfoot and vertical loading force from the tibia acting onto the superior talus work together to mechanically cause a rearfoot 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].

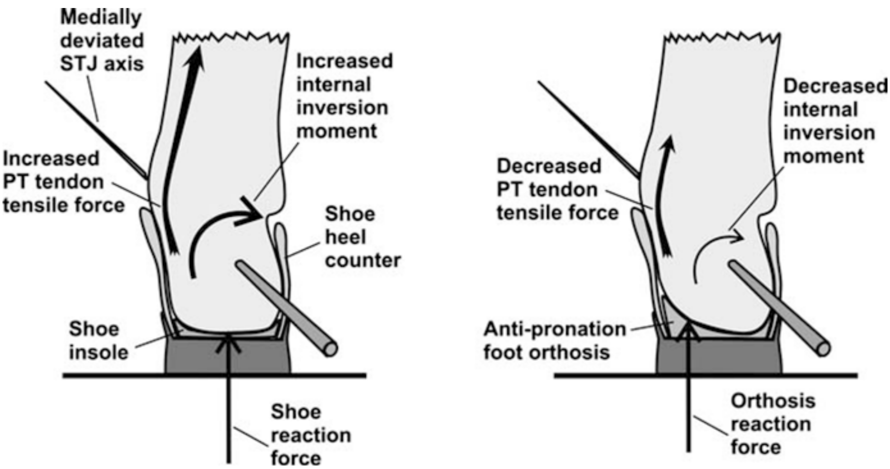

Fig. 2.6 Research has shown that foot orthoses change the kinetics of gait by altering the internal forces acting on the segments of the foot and lower extremity. In the model illustrated above of the posterior aspect of a right foot with a medially deviated STJ axis, when the posterior tibial muscle 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

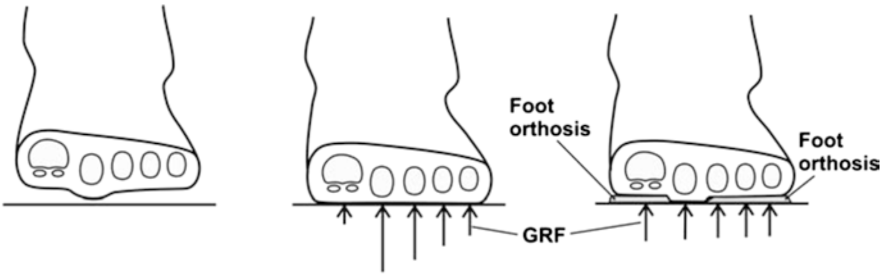

Fig. 2.7 Research has shown that foot orthoses may be designed to reduce the plantar pressures and forces acting on the foot. In the model above, a frontal plane cross section of the metatarsal heads in a foot with a plantarflexed second metatarsal is illustrated. When the forefoot is close to contacting 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.

References

1. Schuster RO. A history of orthopedics in podiatry. J Am Podiatry Assoc. 1974;64:332.
2. Camper P. On the best form of shoe. In: The foot and its covering (trans: James Dowie). London: Hardwicke; 1861. p. xxvii–44. (Translated from Dutch into English).
3. Dorland's illustrated medical dictionary. 25th ed. W.B. Saunders, Philadelphia; 1974.
4. Wu KW. Foot orthoses: principles and clinical applications. Baltimore: Williams and Wilkins; 1990. p. 97.
5. Kirby KA. Foot and lower extremity biomechanics II: Precision Intricast newsletters, 1997–2002. Payson, AZ: Precision Intricast, Inc.; 2002.
6. Durlacher L. A concise treatise on corns, bunions, and the disorders of nails with advice for the general management of the feet. London: Simpkin Marshall and Co; 1845. p. 30.
7. Dagnall JC. History of foot supports. British J Chiropody. 1967;32(1):5–7.
8. Whitman R. Observations of forty-five cases of flat-foot with particular reference to etiology and treatment. Boston Med Surg J. 1888;118:598.
9. Whitman R. The importance of positive support in the curative treatment of weak feet and a comparison of the means employed to assure it. Am J Orthop Surg. 1913;11:215–30.
10. Roberts PW. The initial strain in weak foot, its mechanics, and a new method of treatment. N Y Med J. 1915;102(9):441–2.
11. Morton DJ. The human foot: its evolution, physiology and functional disorders. New York: Columbia University Press; 1935.
12. Levy B. An appliance to induce toe flexion on weight bearing. J Natl Assoc Chirop. 1950; 40(6):24–33.
13. Helfet AJ. A new way of treating flat feet in children. Lancet. 1956;1:262–7.
14. Root ML. How was the Root functional orthotic developed? Podiatry Arts Lab Newsletter. 1981.
15. Root ML. Functional orthoses: hype or help? Pacesetter Magazine, California College of Podiatric Medicine. March–April 1982;2(1):6–12.
16. Root ML. Indications for the use of functional orthoses. Podiatry Arts Lab Newsletter. Pekin, Illinois, Winter 1982.
17. Root ML. Development of the functional orthosis. Clin Podiatr Med Surg. 1994;11: 183–210.
18. Lee WE. Podiatric biomechanics: an historical appraisal and discussion of the Root model as a clinical system of approach in the present context of theoretical uncertainty. Clin Podiatr Med Surg. 2001;18:555–684.
19. Root ML, Orien WP, Weed JH, Hughes RJ. Biomechanical examination of the foot, vol. Volume 1. Los Angeles: Clinical Biomechanics Corporation; 1971.
20. Henderson WH, Campbell JW. U.C.B.L. shoe insert casting and fabrication. Technical report 53. Biomechanics Laboratory, University of California, San Francisco. 1967.
21. Blake RL, Denton JA. Functional foot orthoses for athletic injuries: a retrospective study. J Am Podiatr Med Assoc. 1985;75:359–62.
22. Blake RL. Inverted functional orthoses. J Am Podiatr Med Assoc. 1986;76:275–6.
23. Blake RL, Ferguson H. Foot orthoses for the severe flatfoot in sports. J Am Podiatr Med Assoc. 1991;81:549.
24. Kirby KA. The medial heel skive technique: improving pronation control in foot orthoses. J Am Podiatr Med Assoc. 1992;82:177–88.
25. Kirby KA. Foot and lower extremity biomechanics: a ten year collection of Precision Intricast newsletters. Payson, Arizona: Precision Intricast, Inc.; 1997.
26. Valmassy RL, editor. Clinical biomechanics of the lower extremities. St. Louis: Mosby; 1996.
27. Sackett DL, Rosenberg WMC, Gray JAM, et al. Evidence based medicine: what it is and what it isn't. Br Med J. 1996;312:71–2.
28. Kirby KA. Emerging concepts in podiatric biomechanics. Podiatry Today. 2006;19(12): 36–48.

29. Van Gheluwe B, Kirby KA. Foot biomechanics and podiatry: research meets the clinical world. Footwear Sci. 2009;1:79–80.
30. Van Gheluwe B, Kirby KA. Research and clinical synergy in foot and lower extremity biomechanics. Footwear Sci. 2010;2:111–22.
31. Eggold JF. Orthotics in the prevention of runner's overuse injuries. Phys Sportsmed. 1981;9:181–5.
32. D'Ambrosia RD. Orthotic devices in running injuries. Clin Sports Med. 1985;4:611–8.
33. Dugan RC, D'Ambrosia RD. The effect of orthotics on the treatment of selected running injuries. Foot Ankle. 1986;6:313.
34. Kilmartin TE, Wallace WA. The scientific basis for the use of biomechanical foot orthoses in the treatment of lower limb sports injuries—a review of the literature. Br J Sports Med. 1994;28:180–4.
35. Gross ML, Davlin LB, Evanski PM. Effectiveness of orthotic shoe inserts in the long distance runner. Am J Sports Med. 1991;19:409–12.
36. Saxena A, Haddad J. The effect of foot orthoses on patellofemoral pain syndrome. J Am Podiatr Med Assoc. 2003;93:264–71.
37. Donatelli R, Hurlbert C, Conaway D, St. Pierre R. Biomechanical foot orthotics: a retrospective study. J Orthop Sports Phys Ther. 1988;10:205–12.
38. Moraros J, Hodge W. Orthotic survey: preliminary results. J Am Podiatr Med Assoc. 1993;83:139–48.
39. Walter JH, Ng G, Stoitz JJ. A patient satisfaction survey on prescription custom-molded foot orthoses. J Am Podiatr Med Assoc. 2004;94:363–7.
40. Kusomoto A, Suzuki T, Yoshida H, Kwon J. Intervention study to improve quality of life and health problems of community-living elderly women in Japan by shoe fitting and custom-made insoles. Gerontology. 2007;22:110–8.
41. Franklyn-Miller A, Wilson C, Bilzon J, McCrory P. Foot orthoses in the prevention of injury in initial military training. A randomized controlled trial. Am J Sports Med. 2011;39:30–7.
42. Finestone A, Giladi M, Elad H, et al. Prevention of stress fractures using custom biomechanical shoe orthoses. Clin Orthop Relat Res. 1999;360:182–90.
43. Simkin A, Leichter I, Giladi M, et al. Combined effect of foot arch structure and an orthotic device on stress fractures. Foot Ankle. 1989;10:25–9.
44. Wrobel JS, Fleischer AE, Crews RT, Jarret B, Najafi B. A randomized controlled trial of custom foot orthoses for the treatment of plantar heel pain. J Am Podiatr Med Assoc. 2015;105(4):281–94.
45. Gross MT, Byers JM, Krafft JL, et al. The impact of custom semirigid foot orthotics on pain and disability for individuals with plantar fasciitis. J Orthop Sports Phys Ther. 2002;32:149–57.
46. Collins N, Crossley K, et al. Foot orthoses and physiotherapy in the treatment of patellofemoral pain syndrome: randomised clinical trial. Br J Sports Med. 2009;43:169–71.
47. Eng JJ, Pierrynowski MR. Evaluation of soft foot orthotics in the treatment of patellofemoral pain syndrome. Phys Ther. 1993;73:62–70.
48. Barton CJ, Menz HB, Crossley KM. The immediate effects of foot orthoses on functional performance in individuals with patellofemoral pain syndrome. Br J Sports Med. 2011;45:193–7.
49. Mills K, et al. A randomised control trial of short term efficacy of in-shoe foot orthoses compared with a wait and see policy for anterior knee pain and the role of foot mobility. Br J Sports Med. 2011;46:247–52.
50. Thompson JA, Jennings MB, Hodge W. Orthotic therapy in the management of osteoarthritis. J Am Podiatr Med Assoc. 1992;82:136–9.
51. Halstead J, Keenan AM, McGonagle D, Conaghan P, Redmond A. An exploration into the effect of foot orthoses on bone marrow lesions associated with mechanical foot pain. J Foot Ankle Res. 2014;7(Suppl 2):A1. http://www.footankleres.com/content/7/A1.
52. Slattery M, Tinley P. The efficacy of functional foot orthoses in the control of pain and ankle joint disintegration in hemophilia. J Am Podiatr Med Assoc. 2001;91:240–4.

53. Chalmers AC, Busby C, Goyert J, et al. Metatarsalgia and rheumatoid arthritis-a randomized, single blind, sequential trial comparing two types of foot orthoses and supportive shoes. J Rheumatol. 2000;27:1643–7.
54. Woodburn J, Barker S, Helliwell PS. A randomized controlled trial of foot orthoses in rheumatoid arthritis. J Rheumatol. 2002;29:1377–83.
55. Mejjad O, Vittecoq O, Pouplin S, et al. Foot orthotics decrease pain but do not improve gait in rheumatoid arthritis patients. Joint Bone Spine. 2004;71:542–5.
56. Powell M, Seid M, Szer IA. Efficacy of custom foot orthotics in improving pain and functional status in children with juvenile idiopathic arthritis: a randomized trial. J Rheumatol. 2005;32:943–50.
57. Coda A, Fowlie PW, Davidson JE, Walsh J, Carline T, Santos D. Foot orthoses in children with juvenile idiopathic arthritis: a randomised controlled trial. Arch Dis Child. 2014; 99(7):649–51. doi:10.1136/archdischild-2013-305166.
58. Burns J, Crosbie J, Ouvrier R, Hunt A. Effective orthotic therapy for the painful cavus foot. J Am Podiatr Med Assoc. 2006;96:205–11.
59. Postema K, Burm PE, Zande ME, Limbeek J. Primary metatarsalgia: the influence of a custom moulded insole and a rockerbar on plantar pressure. Prosthet Orthot Int. 1998;22: 35–44.
60. Hodge MC, Bach TM, Carter GM. Orthotic management of plantar pressure ad pain in rheumatoid arthritis. Clin Biomech. 1999;14:567–75.
61. Raspovic A, et al. Effect of customized insoles on vertical plantar pressures in sites of previous neuropathic ulceration in the diabetic foot. Foot. 2000;10:133–8.
62. Li CY, et al. Biomechanical evaluation of foot pressure and loading force during gait in RA patients with and without foot orthoses. Kurume Med J. 2000;47:211–7.
63. Lobmann R, et al. Effects of preventative footwear on foot pressure as determined by pedobarography in diabetic patients: a prospective study. Diabet Med. 2001;18:314–9.
64. Duffin AC, Kidd R, Chan A, Donaghue KC. High plantar pressure and callus in diabetic adolescents. Incidence and treatment. J Am Podiatr Med Assoc. 2003;93:214–20.
65. Pham T, et al. Laterally elevated wedged insoles in the treatment of medial knee OA: a two-year prospective randomized controlled study. Osteoarthritis Cartilage. 2004;12:46–55.
66. Rubin R, Menz HB. Use of laterally wedged custom foot orthoses to reduce pain associated with medial knee osteoarthritis: a preliminary investigation. J Am Podiatr Med Assoc. 2005;95:347–52.
67. Crenshaw SJ, Pollo FE, Calton EF. Effects of lateral-wedged insoles on kinetics at the knee. Clin Orthop Relat Res. 2000;375:185–92.
68. Butler RJ, Marchesi S, Royer T, Davis IS. The effect of a subject-specific amount of lateral wedge on knee mechanics in patients with medial knee osteoarthritis. J Orthop Res. 2007; 25(9):1121–7.
69. Hinman RS, Bowles KA, Payne C, Bennell KL. Effect of length on laterally-wedged insoles in knee osteoarthritis. Arthritis Care Res. 2008;59(1):144–7.
70. Shelburne KB, Torry MR, Steadman JR, Pandy MG. Effects of foot orthoses and valgus bracing on the knee adduction moment and medial joint load during gait. Clin Biomech. 2008;23(6):814–21.
71. Hinman RS, Payne C, Metcalf BR, Wrigley TV, Bennell KL. Lateral wedges in knee osteoarthritis: what are their immediate clinical and biomechanical effects and can these predict a three-month clinical outcome? Arthritis Care Res. 2008;59(3):408–15.
72. Butler RJ, Barrios JA, Royer T, Davis IS. Effect of laterally wedged foot orthoses on rearfoot and hip mechanics in patients with medial knee osteoarthritis. Prosthet Orthot Int. 2009;33(2):107–16.
73. Russell EM, Hamill J. Lateral wedges decrease biomechanical risk factors for knee osteoarthritis in obese women. J Biomech. 2011;44(12):2286–91.
74. Hinman RS, Bowles KA, Metcalf BB, Wrigley TV, Bennell KL. Lateral wedge insoles for medial knee osteoarthritis. Effects on lower limb frontal plane biomechanics. Clin Biomech. 2012;27(1):27–33.

75. Fantini Pagani CH, Hinrichs M, Bruggermann GP. Kinetic and kinematic changes with the use of valgus knee brace and lateral wedge insoles in patietns with medial knee osteoarthritis. J Orthop Res. 2012;30(7):1125–32.
76. Hsu WC, Jhong YC, Chen HL, et al. Immediate and long-term efficacy of laterally-wedged insoles on persons with bilateral medial knee osteoarthritis during walking. Biomed Eng Online. 2015;14(1):43. doi:10.1186/s12938-015-0040-6.
77. Kakihana W, Akai M, Yamasaki N, Takashima T, Nakazawa K. Changes of joint moments in the gait of normal subjects wearing lateral wedged insoles. Am J Phys Med Rehabil. 2004;83:273–8.
78. Kakihana W, Akai M, Nakazawa K, Takashima T, Naito K, Torii S. Effects of laterally wedged insoles on knee and subtalar joint moments. Arch Phys Med Rehabil. 2005;86(7): 1465–71.
79. Haim A, Wolf A, Rubin G, Genis Y, Khoury M, Rozen N. Effect of center of pressure modulation on knee adduction moment in medial compartment knee osteoarthritis. J Orthop Res. 2011;29(11):1668–74.
80. Shimada S, Kobayashi S, Wada M, et al. Effects of disease severity on response to lateral wedged shoe insole for medial compartment knee osteoarthritis. Arch Phys Med Rehabil. 2006;87(11):1436–41.
81. Van Raaij TM, Reigman M, Brouwer RW, Bierma-Zeinstra SMA, Verhaar JAN. Medial knee osteoarthritis treated by insoles or braces: a randomized trial. Clin Orthop Relat Res. 2010;468:1926–32.
82. Rafiaee M, Karimi MT. The effects of various kinds of lateral wedge insoles on performance of individuals with knee joint osteoarthritis. Int J Prev Med. 2012;3(10):693–8.
83. Skou ST, Hojgaard L, Simonsen OH. Customized foot insoles have a positive effect on pain, function, and quality of life in patients with medial knee osteoarthritis. J Am Podiatr Med Assoc. 2013;103(1):50–5.
84. Marks R, Penton L. Are foot orthotics efficacious for treating painful medial compartment knee osteoarthritis? A review of the literature. Int J Clin Pract. 2004;58:49–57.
85. Guskiewicz KM, Perrin DH. Effects of orthotics on postural sway following inversion ankle sprain. J Orthop Sports Phys Ther. 1996;23:326–31.
86. Hertel J, Denegar CR, et al. Effect of rearfoot orthotics on postural control in healthy subjects. J Sport Rehabil. 2001;10:36–47.
87. Rome K, Brown CL. Randomized clinical trial into the impact of orthoses on balance parameters in excessively pronated feet. Clin Rehabil. 2004;18:624–30.
88. Gross MT, Mercer VS, Lin FC. Effects of foot orthoses on balance in older adults. J Orthop Sports Phys Ther. 2012;42(7):649–57.
89. De Morais BC, et al. The effect of foot orthoses on balance, foot pain and disability in elderly women with osteoporosis: a randomized clinical trial. Rheumatology (Oxford). 2013;52(3): 515–22.
90. Rose GK. Correction of the pronated foot. J Bone Joint Surg. 1958;40B:674–83.
91. Rose GK. Correction of the pronated foot. J Bone Joint Surg. 1962;44B:642–7.
92. Sgarlato TE, editor. A compendium of podiatric biomechanics. San Francisco: California College of Podiatric Medicine; 1971.
93. Kirby KA, Green DR. Evaluation and nonoperative management of pes valgus. In: DeValentine S, editor. Foot and ankle disorders in children. New York: Churchill-Livingstone; 1992. p. 295–327.
94. Root ML, Weed JH. Personal communication. 1984.
95. Kirby KA. Methods for determination of positional variations in the subtalar joint axis. J Am Podiatr Med Assoc. 1987;77:228–34.
96. De Schepper J, Van Alsenoy K, Rijckaert J, De Mits S, Lootens T, Roosen P. Intratest reliability in determining the subtalar joint axis using the palpation technique described by K. Kirby. J Am Podiatr Med Assoc. 2012;102(2):122–9.

97. Van Alsenoy KK, D'Août K, Vereecke E, De Schepper J, Santos D. The subtalar joint axis palpation technique: Part 2—results on reliability and validity using cadaver feet. J Am Podiatr Med Assoc. 2014;104(4):365–74.
98. Kirby KA. Rotational equilibrium across the subtalar joint axis. J Am Podiatr Med Assoc. 1989;79:1–14.
99. Kirby KA. Subtalar joint axis location and rotational equilibrium theory of foot function. J Am Podiatr Med Assoc. 2001;91:465–88.
100. Blake RL, Ferguson H. The inverted orthotic technique: its role in clinical biomechanics. In: Valmassy RL, editor. Clinical biomechanics of the lower extremities. St. Louis: Mosby-Year Book; 1996. p. 465–97.
101. Bonanno DR, Zhang CY, Farrugia RC, Bull MG, Raspovic AM, Bird AR, Landorf KB. The effect of different depths of medial heel skive on plantar pressures. J Foot Ankle Res. 2012;5(Suppl 1):20. doi:10.1186/1757-1146-5-20.
102. Harradine P, Collins S, Webb C, Bevan L. The medial oblique shell inclination technique: a method to increase subtalar supination moments in foot orthoses. J Am Podiatr Med Assoc. 2011;101(6):523–30.
103. Gardner C, Coull D, Coull R. DC inverted wedge technique. http://www.equusmedical.com/DCInverted/dcinver.htm. Accessed 30 Aug 2015.
104. Landorf K, Keenan AM, Rushworth AL. Foot orthosis prescription habits of Australian and New Zealand podiatric physicians. J Am Podiatr Med Assoc. 2001;91(4):174–83.
105. Kirby KA. Lateral heel skive orthosis technique. Precision Intricast newsletter. Payson, AZ: Precision Intricast, Inc.; September 2004.
106. Nigg BM. The assessment of loads acting on the locomotor system in running and other sports activities. Semin Orthop. 1988;3(4):197–206.
107. Nigg BM, Bobbert M. On the potential of various approaches in load analysis to reduce the frequency of sports injuries. J Biomech. 1990;23:3–12.
108. Morlock M, Nigg BM. Theoretical consideration and practical results on the influence of the representation of the foot for the estimation of internal forces with models. Clin Biomech. 1991;6:3–13.
109. McPoil TG, Hunt GC. Evaluation and management of foot and ankle disorders: present problems and future directions. J Orthop Sports Phys Ther. 1995;21:381–8.
110. Fuller EA. Computerized gait evaluation. In: Valmassy RL, editor. Clinical biomechanics of the lower extremities. St. Louis: Mosby-Year Book; 1996. p. 179–205.
111. Fuller EA. Center of pressure and its theoretical relationship to foot pathology. J Am Podiatr Med Assoc. 1999;89(6):278–91.
112. Fuller EA: Reinventing biomechanics. Podiatry Today. December 2000;13(3).
113. Fuller EA, Kirby KA. Subtalar joint equilibrium and tissue stress approach to biomechanical therapy of the foot and lower extremity. In: Albert SF, Curran SA, editors. Biomechanics of the lower extremity: theory and practice, vol. 1. Denver: Bipedmed LLC; 2013. p. 205–64.
114. Kirby KA. Are Root biomechanics dying? Podiatry Today. 2009;22(4).
115. Kirby KA. Has tissue stress theory supplanted Root theory? Podiatry Today. 2015;34(4):36–44.
116. Nigg BM, Nurse MA, Stefanyshyn DJ. Shoe inserts and orthotics for sport and physical activities. Med Sci Sports Exerc. 1999;31(7 Suppl):S421–8.
117. Nigg BM. The role of impact forces and foot pronation: a new paradigm. Clin J Sport Med. 2001;11:2–9.
118. Nigg BM, Baltich J, Hoerzer S, Enders H. Running shoes and running injuries: mythbusting and a proposal for two new paradigms: 'preferred movement path' and 'comfort filter'. Br J Sports Med. 2015. doi:10.1136/bjsports-2015-095054.
119. Payne CB. The past, present, and future of podiatric biomechanics. J Am Podiatr Med Assoc. 1998;88:53–63.

120. Bates BT, Osternig LR, Mason B, James LS. Foot orthotic devices to modify selected aspects of lower extremity mechanics. Am J Sports Med. 1979;7:328–31.
121. Smith LS, Clarke TE, Hamill CL, Santopietro F. The effects of soft and semi-rigid orthoses upon rearfoot movement in running. J Am Podiatr Med Assoc. 1986;76:227–32.
122. Novick A, Kelley DL. Position and movement changes of the foot with orthotic intervention during loading response of gait. J Orthop Sports Phys Ther. 1990;11:301–12.
123. McCulloch MU, Brunt D, Linden DV. The effect of foot orthotics and gait velocity on lower limb kinematics and temporal events of stance. J Orthop Sports Phys Ther. 1993;17:2–10.
124. Butler RJ, McClay-Davis IS, Laughton CM, Hughes M. Dual-function foot orthosis: effect on shock and control of rearfoot motion. Foot Ankle Int. 2003;24:410–4.
125. Laughton CA, McClay-Davis IS, Hamill J. Effect of strike pattern and orthotic intervention on tibial shock during running. J Appl Biomech. 2003;19:153–16.
126. Mundermann A, Nigg BM, Humble RN, Stefanyshyn DJ. Foot orthoses affect lower extremity kinematics and kinetics during running. Clin Biomech. 2003;18:254–62.
127. Williams DS, McClay-Davis I, Baitch SP. Effect of inverted orthoses on lower extremity mechanics in runners. Med Sci Sports Exerc. 2003;35:2060–8.
128. MacLean CL, Hamill J. Short and long-term influence of a custom foot orthotic intervention on lower extremity dynamics in injured runners. Annual ISB meeting, Cleveland, September 2005.
129. Eng JJ, Pierrynowski MR. The effect of soft foot orthotics on three-dimensional lower-limb kinematics during walking and running. Phys Ther. 1994;74:836–44.
130. Johanson MA, Donatelli R, Wooden MJ, Andrew PD, Cummings GS. Effects of three different posting methods on controlling abnormal subtalar pronation. Phys Ther. 1994;74:149–58.
131. Fong DTP, Lam MH, Lao MLM, et al. Effect of medial arch-heel support in inserts on reducing ankle eversion: a biomechanical study. J Orthop Surg Res. 2008;3:7–13.
132. MacLean CL, Davis IS, Hamill J. Short and long-term influences of a custom foot orthotic intervention on lower extremity dynamics. Clin J Sport Med. 2008;18:338–43.
133. Nester CJ, Hutchins S, Bowker P. Effect of foot orthoses on rearfoot complex kinematics during walking gait. Foot Ankle Int. 2001;22:133–9.
134. Nester CJ, Van Der Linden ML, Bowker P. Effect of foot orthoses on the kinematics and kinetics of normal walking gait. Gait Posture. 2003;17:180–7.
135. MacLean C, Davis IM, Hamill J. Influence of a custom foot intervention on lower extremity dynamics in healthy runners. Clin Biomech. 2006;21:621–30.
136. Nawoczenski DA, Cook TM, Saltzman CL. The effect of foot orthotics on three-dimensional kinematics of the leg and rearfoot during running. J Orthop Sports Phys Ther. 1995;21:317–27.
137. Stackhouse CL, Davis IM, Hamill J. Orthotic intervention in forefoot and rearfoot strike running patterns. Clin Biomech. 2004;19:64–70.
138. Woodburn J, Helliwell PS, Barker S. Changes in 3D joint kinematics support the continuous use of orthoses in the management of painful rearfoot deformity in rheumatoid arthritis. J Rheumatol. 2003;30:2356–64.
139. Nawoczenski DA, Ludewig PM. Electromyographic effects of foot orthotics on selected lower extremity muscles during running. Arch Phys Med Rehabil. 1999;80:540–4.
140. Tomaro J, Burdett RG. The effects of foot orthotics on the EMG activity of selected leg muscles during gait. J Orthop Sports Phys Ther. 1993;18:532–6.
141. Mundermann A, Wakeling JM, Nigg BM, et al. Foot orthoses affect frequency components of muscle activity in the lower extremity. Gait Posture. 2006;23:295–302.
142. Mundermann A, Nigg BM, Humble RN, Stefanyshyn DJ. Orthotic comfort is related to kinematics, kinetics, and EMG in recreational runners. Med Sci Sports Exerc. 2003;35:1710–9.
143. Dedieu P, Drigeard C, Gjini L, Maso FD, Zanone PG. Effects of foot orthoses on the temporal pattern of muscular activity during walking. Clin Biomech. 2013;28(7):820–4.
144. Cheung JT, Zhang M. A 3-dimensional finite element model of the human foot and ankle for insole design. Arch Phys Med Rehabil. 2005;86:353–8.

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