# Evolution of Foot Orthotics—Part 2: Research Reshapes Long-Standing Theory

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## Abstract

**Objective:** To challenge casual understanding of the causal mechanisms of foot orthotics. Although the classic orthotic paradigm of Merton L. Root and his colleagues is often acknowledged, the research attempting to explain and validate these mechanisms is far less clear in its appraisal.

**Data Sources:** Studies evaluating the relationship of foot type (medial arch height) and use of foot orthoses to the motions of the foot and ankle were compared and contrasted. A search was conducted to evaluate other possible mechanisms of orthotic intervention.

**Results:** Although Root's methods of foot evaluation (subtalar neutral position) and casting (non–weight-bearing) are well referenced, these methods have poor reliability, unproven validity, and are, in fact, seldom strictly followed. We challenge 2 widely held concepts: that excessive foot eversion leads to excessive pronation and that orthotics provide beneficial effects by controlling rearfoot inversion/eversion. Numerous studies show that patterns of rearfoot inversion/eversion cannot be characterized either by foot type or by orthotics use. Rather, subtle control of internal/external tibial rotation appears to be the most significant factor in maintaining proper supination/pronation mechanics. Recent evidence also suggests that proprioceptive influences play a large, and perhaps largely unexplored, role.

**Conclusions:** Considerable evidence supports the exploration of new theories and paradigms of orthotics use. Investigations of flexible orthotic designs, proprioceptive influences, and the 3-dimensional effects of subtalar joint motion on the entire kinetic chain are areas of research that show great promise. (J Manipulative Physiol Ther 2002;25:125-34)


**Key Indexing Terms:** *Biomechanics; Orthotic Devices; Foot and Ankle; Subtalar Joint*

## Introduction

Epidemiologic studies on the use of foot orthoses report numerous clinical successes for the treatment of foot, ankle, and other skeletal alignment problems.[1] Foot orthoses have been successfully used to treat various lower extremity symptoms, including knee pain, plantar fasciitis, shinsplints, and iliotibial band tendinitis.[2] Recent studies also confirm the use of foot orthoses to treat low back pain.[3,4] The clinical literature contains numerous descriptions of detailed methods that may be used to prescribe, fabricate, and fit foot orthoses. A common thread[5] throughout much of this literature is the routine deference to the classic works of Root et al.[6] In these texts from the 1970s, clinicians were advised to conduct non–weight-bearing assessments of a patient's subtalar joint with the purpose of finding its neutral position. The pathologic condition of the foot and, hence, the patient's need for an orthotic were to be assessed from this starting position. With the foot held in the subtalar neutral position, a plaster cast could be made of the foot's shape; then, an orthotic device could be fabricated from rigid or semi-rigid materials on the basis of impressions made in the cast. Today, some clinicians in various health professions believe that strict adherence to this approach may be essential for the production of quality orthoses. Yet strangely, although Root's approach has gained considerable clinical acceptance, research over the past 30 years has all but struggled to provide mechanistic support for even the most basic of Root's orthotic concepts.[7-9] Consider that the supposed importance of the subtalar neutral position has never been validated.[10,11] Indeed, recent analysis suggests that orthoses made by use of the subtalar neutral approach inherently favor supination, despite the "neutral" intent of this practice.[9] Additionally, as this article will demonstrate, even the principle tenet that orthoses control rearfoot motion can be seriously ques-

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tioned.[12-14] Furthermore, clinical successes have been gained with alternative orthotic paradigms that differ quite substantially from the classic Root approach. Thus, despite the best efforts of Merton L. Root and others, the scientific research devoted to explaining orthotic interventions remains mired in controversy. The mechanisms of cause and effect, those through which orthotics truly improve patient health, remain elusive.[2,7,8]

Despite healthy skepticism,[15] it is the aim of many researchers to turn the use of foot orthoses from its traditional status as a specialized clinical art into a well-practiced clinical science. Therefore, this article presents a review of scientific studies that have been conducted in the areas of clinical assessment and the use of foot orthoses as they relate to the motions of the foot and ankle. Criticisms are made with respect to the various current theoretical paradigms of orthotic intervention. The primary focus is on exploring the potential mechanisms that may be used to explain the numerous clinical successes of foot orthoses. Finally, suggestions regarding the direction of future research are offered.

## Discussion

Over the past 3 decades, guided principally by Root's methodologies, many researchers have attempted to determine the relationships existing between variations in foot and ankle structure, orthotic interventions, and the compensatory effects that occur within the dynamic function of the foot, ankle, and lower extremities. In particular, specific attempts have been made to justify the use of static classification schemes as a means of predicting dynamic joint function. Unfortunately, these attempts have met with mixed results.

### Poor Prediction of Rearfoot Inversion/Eversion

In 1989, Hamill et al[12] studied the knee and rearfoot motion of 24 normal subjects as they walked barefoot. Following the standard clinical practices outlined by Root, they performed 16 static foot and lower extremity measurements on each subject. Unfortunately, approximately one third of this study's clinical measures were discarded because of poor clinical reliability. From the remaining data, a statistical correlation was determined with the intent of quantifying the strength of the relationship between the subjects' actual rearfoot motion (measured as inversion/eversion) versus the subjects' expected motion patterns as predicted by Root's classification scheme. Unfortunately, Hamill et al[12] were not able to arrive at statistically valid results. Taking up the challenge, McPoil and Cornwall[13] published a similar study in 1996. In their work, 17 static measurements (16 similar to those above and 1 additional) were performed bilaterally on the lower extremities of 27 typical healthy subjects. Videotape analysis was used to determine the maximum amount of rearfoot pronation that each subject exhibited while walking. Multiple regression analysis was performed in an attempt to link the clinical and motion data. The results showed that only 1 static measurement was significantly related to maximal dynamic rearfoot motion. This measurement, described as the "difference in navicular height," was specifically created by McPoil and Cornwall[13] for the purposes of quantifying the changes that occurred in navicular height when a subject stood first in a weight-bearing subtalar neutral position and, second, in a relaxed standing position. All of the remaining 16 static measurements (originated by Root and colleagues) were found to be poor predictors of both maximum pronation and the time to maximum pronation.

Next to the more general dimensions of length and width, the height of the medial longitudinal arch is probably the most commonly described characteristic when assessments are done of an individual's foot and is often categorized as high, normal, or low arch. Razeghi and Batt[8] note, "It is widely believed that a low arched foot tends to be more flexible, and thus, is subject to increased pronation (amount, timing and/or velocity). In contrast, a high arched foot is known to be more rigid and consequently exhibits increased supination." Thus, the literature has long maintained an interest in the investigation of arch height (foot type) and its effects on motion patterns.

### Effects of Foot Type Appear Unclear

In a study attempting to relate foot type classification with the prediction of rearfoot inversion/eversion motion, Knutzen and Price[14] examined the gait patterns of 20 nonsymptomatic subjects. The subjects were selected specifically to span the breadth of foot types. After classifying each individual's foot type, they analyzed each subjects' gait pattern with a high-speed camera to record rearfoot motion in the frontal plane and an electrogoniometer to determine related sagittal plane motions at the hip, knee, and ankle. The results of this study were similar to those of Hamill et al[12] and McPoil and Cornwall.[13] Regression analysis showed that foot type was not statistically related to rearfoot (inversion/eversion) motion. This was true at both heel strike and at maximum rearfoot angle. Interestingly, measures of hip joint movement were found to best predict rearfoot angle. One plausible explanation for this finding is that longitudinal rotations coincidental with hip movements may have produced variation in the orientation of the long axis of the foot with respect to the ground.[16] Considering this study's emphasis on frontal plane analysis, plantar/dorsiflexion at the ankle could have been partially interpreted as having produced variation in the rearfoot angle.

In 2000, Razeghi and Batt[8] published a review article that focused specifically on the combined topics of foot type, injury rates, and orthotic intervention. This article covered many issues and should be consulted directly by those with an interest in these topics; however, a few points can be reiterated. First, although there is reasonable evidence to suggest that an individual's foot type predisposes him or her to certain types of overuse injuries,[17,18] the mechanisms through which arch height variation and orthotic interventions affect injury rates are poorly understood. Second, contradictory to conventional thought,[19] research does not actually support the argument that low-arched feet are more prone to injury. Rather, "prospective studies by Cowan et al on US Army trainees. . . suggested that low-arched feet provide protection against lower-limb injury."[8] Third, according to several epidemiologic studies conducted on runners,[20] the various clinical measures of lower extremity alignment that are commonly implicated as being major risk factors have not been found to be statistically related to injury rates.[21] Clearly, all such findings conflict with the traditional views that are commonly held with respect to the influences of foot type.

### 3-Dimensional Studies Implicate Tibial Rotation

A recent study by Nawoczenski et al[22] used advanced 3-dimensional (3-D) measurement technology to determine the effects of foot type on running. After examining the running patterns of 20 subjects who had undergone detailed radiographic examinations of their foot type, they confirmed that similar rearfoot inversion/eversion patterns were produced by the high- and low-arched groups (n = 10 each). Because of the 3-D nature of this study, Nawoczenski et al[22] also quantified the internal/external rotation of the tibia relative to the rearfoot (labeled as medial/lateral rotation). Here, the 2 groups produced distinctly different patterns; specifically, the high-arched individuals showed greater ranges of tibial longitudinal rotation.

In another article, Nawoczenski et al[2] investigated the effects of foot orthotics on the 3-D kinematics of the leg and rearfoot during running. In this study, the same 20 subjects previously described[22] were evaluated with and without the use of custom rigid orthoses. The results of this study indicated that the major effects of the orthoses occurred within the first 50% of the stance phase. Again, with respect to rearfoot inversion/eversion patterns, no significant differences were found between the high- and low-arched groups. Use of the orthoses did, however, produce a small but significant change in the rotation of the tibia relative to the rearfoot. Specifically, the orthoses reduced the total range of tibial medial/lateral rotation by approximately 2°. Surprisingly, both the high- and low-arched groups experienced similar reductions in tibial rotation range.

In the studies discussed thus far, inaccuracies in estimating the body's underlying skeletal motion may have occurred as a result of the common use of surface markers. Muscular activity inherently induces shifts in soft tissue. Joint motion often accompanies muscular activity, and both of these events induce skin movement. Because markers are commonly attached to the skin during kinematic analyses, routine events within the human body can be expected to alter marker positions, thereby producing motion artifacts.[23,24] In an effort to avoid such problems, Stacoff et al[25] recently conducted an orthotics study that used invasive procedures. Marker clusters were affixed to the surfaces of the skin, the shoe, and to rigid pins that had been surgically inserted into the calcaneus and tibia of volunteer subjects. The intent of this study was to first capture the combined motions of the talocrural and subtalar joints and then to quantify the errors that are made when one relies only on the measurements of skin and shoe motion. Note that, despite the use of bone pins, only the "combined" motions of the foot and ankle could be quantified. The motion of the talus, situated between the calcaneus and the tibia, cannot be directly measured because of its intimate location. Because of the invasive nature of this study, only 5 young healthy subjects participated. Although the individual orthopedic characteristics (foot types) of the subjects were not reported, Stacoff et al[25] commented that none of the subjects was an overpronator. The orthoses tested in this study were relatively simple by design. Two styles of medial posting were applied to standard shoe inserts. One style involved the mid-sole placement of a semicircular wedge (20°) made of cork, whereas the second used a more posterior placement of the same size wedge under the sustentaculum tali. With respect to the kinematic results, Stacoff et al[25] reported that a great deal of variability occurred across the subject group. In fact, the individual variability among the subjects exceeded the magnitudes of the kinematic effects that were produced by the orthoses. No significant differences were found between the 2 styles of posting (mid-sole, posterior). Again, the changes in inversion/eversion produced by the orthoses were small. Indeed, the only statistically significant kinematic result produced by the orthoses was that of a small reduction (1°-4°) in maximal tibial internal rotation. Essentially, these in vivo results appeared to confirm the findings of Nawoczenski et al.[2]

### Movement Coupling Within the Subtalar Joint

Given the previous attention paid by Root and others to various (coronal plane) alignment issues such as rearfoot/forefoot varus/valgus,[26] it should seem surprising that alterations in tibial rotation and not inversion/eversion were the most consistent finding in the above 3-D studies. From these studies,[27-30] it would appear that longitudinal rotations play a much more pivotal role in running, and perhaps even walking, performance. Fortunately, the classic texts on human gait by Inman[31] and others[32] provide a useful explanation for this phenomenon. In these works, Inman and his colleagues clarified the importance and complexities of the motions of the foot and ankle. Of these, the geometry of the subtalar joint appears to be the most important factor.

The axis of rotation of the subtalar joint lies generally in an anteroposterior direction, yet it is oblique to all 3 of the anatomic planes. Noting that considerable variability does exist, Inman[31] reported from cadaveric studies that the subtalar axis possesses an average elevation of 42° in the sagittal plane. In the transverse plane this same axis of rotation is oriented approximately 23° medial to the long axis of the foot. Inman et al[32] chose the words "mitered hinge" to describe the actions of the subtalar joint. Specifically, pure rotation around the long axis of one segment (rearfoot inversion/eversion) causes rotation around a completely different axis in the segment at the other end of the joint (tibial internal/external rotation). In this manner, routine patterns of rearfoot inversion/eversion manifest themselves as specific patterns of tibial medial/lateral rotation. However, since contact with the ground specifically limits the range of inversion/eversion, it is the geometry of the subtalar joint that governs the transference into tibial rotation.

In recent studies that use 3-D–movement analysis, the term "movement coupling" has been created to describe the functional significance of the subtalar joint.[22,33,34] Nigg et al[33] defined "movement coupling" as the ratio between the maximal amount of foot eversion and the maximal medial rotation in the tibia for each given subject. They proposed that individuals with a low ratio would demonstrate a high transfer into tibial rotation. They further hypothesized that large amounts of tibial rotation could be a potential cause of knee pain because compensation at the tibiofemoral joint would presumably be required. Nigg et al[33] evaluated the statistical relationship between movement coupling and the height of the medial longitudinal arch in an attempt to identify a predictive clinical indicator of knee injury. Unfortunately, only a weak relationship was demonstrated; arch height explained only 27% of the variance in movement coupling.

Borrowing on Nigg's work, Nawoczenski et al[22] used the concept of movement coupling in their 1998 study to explain the kinematic differences they noted between high- and low-foot groups. Specifically, they hypothesized that the low-foot group produced a smaller range of tibial rotation because the subtalar axes in these subjects were aligned more closely with the foot's true inversion/eversion (long) axis. In contrast, the subtalar geometry of the high-foot type was believed to have permitted a greater transfer into tibial rotation because no inversion/eversion differences were found between the high- and low-foot groups.

## Movement Coupling and Orthotic Interventions

With respect to explaining the modest effects of orthotics on tibial rotation, the usefulness of the movement-coupling concept appears more limited. In Nawoczenski's study on orthotics[2] described previously, the tibial rotation range showed a reduction of only 2°. A simple application of the movement-coupling theory suggests that the inversion/eversion range should also have been reduced; however, this alteration was not seen. Nawoczenski et al[2] found that both foot types responded similarly to their orthotic interventions. Such a response would not have been expected given the distinct geometric differences of the foot types. The findings of Stacoff et al,[25] described previously, also appear to be somewhat inconsistent with respect to the movement-coupling theory. The use of orthotics produced a small reduction (1°-4°) in maximal tibial internal rotation, yet changes in inversion/eversion were judged to be insignificant. There are, however, a few possible explanations for such apparent inconsistencies.

Besides the obvious use of bone pins, a few differences exist between the reports of Stacoff et al[25] and Nawoczenski et al.[2] Although both studies reported changes in tibial rotation as their major findings, Stacoff et al reported values of maximal internal (medial) rotation, whereas the findings of Nawoczenski et al dealt exclusively with measurements of total range. Thus, the subjects of Nawoczenski et al may have shown an unreported reduction in medial rotation. A second difference involves the characteristics of the subjects and their orthotic treatments. Nawoczenski et el[2] rigorously categorized their subjects in terms of foot type. Each subject was provided with custom-fitted orthoses. The subjects in the study by Stacoff et al,[25] however, were uncharacterized with respect to arch height, and the orthoses used were also relatively simple (insert with wedge). Stacoff et al reported great variability in their kinematic findings. With respect to the nonorthotic condition, this variability was perhaps representative of variation within the foot types of the subject group. If so, considerable variability would be expected in response to the use of generic orthoses. Additionally, less than optimal responses to the orthotic intervention would likely lead to an underestimation in the reduction of maximal tibial rotation. We contend that Stacoff's study could have been more informative if custom-fitted orthoses had been used.

Concern may also be expressed with respect to the original design of the movement-coupling concept itself.[33] In their studies on running, Nigg et al[33] compared values of maximal rearfoot eversion with values of maximal tibial medial rotation for each given subject. At a practical level, such measures would rarely (if ever) be obtained together at the same instant. Thus, the current method of calculating movement coupling produces comparisons that are quite likely temporally invalid. Additionally, the use of maximal values in both directions (eversion and medial rotation) can lead to misrepresentation of the actual importance of each range of motion. Essentially, movements of inversion and lateral rotation are completely ignored. In future studies, researchers should devise movement comparisons that are temporally or functionally more meaningful. Because the movement coupling concept conveys a measure of tibial transference, simple comparisons of the total ranges of the 2 patterns (rearfoot inversion/eversion vs tibial medial/lateral rotation) may prove useful.

## Measurement/Modeling of the Subtalar Joint

If one could gain complete knowledge of the geometry and function of the subtalar joint, it is likely that a detailed understanding of the input/output mechanisms of orthotic interventions would follow. As Root, Inman, and others had theorized, the subtalar joint represents the biomechanical gateway between the motions of the foot and the rest of the body.[9] Several researchers since that time have attempted to devise methods of measuring and modeling the geometry and motion of the subtalar joint. In 1964, Wright et al[35] created a hinged cast that could monitor the motions of the subject's underlying foot and ankle joints. To permit such measurements, Wright et al found it necessary to painstakingly align and realign the hinges of their device until it moved freely over the subtalar joint without binding from malalignment. They published representative gait data for the foot and ankle, which showed that the subtalar joint was essentially in the same position both at mid-stance and during relaxed standing. It was these results that Root and his colleagues mistakenly interpreted when they created the subtalar neutral concept.[9]

Although the device that Wright et al[35] created was mechanically innovative, this approach was quite impractical for routine use. In response, Scott and Winter[36] developed a protocol that could be used to compute 3-D kinematic estimates of the axes of rotation of both the subtalar and talocrural joints. Again, a repetitive trial-and-error process was used; however, the application of this technique was much simpler. By rotating each subject's foot through the neutral range of its subtalar motion, Scott and Winter were able to quickly arrive at gross estimates of the orientation of the subtalar joint. The skin surface relative to each region of interest was then examined to find specific locations that did not move. These locations were believed to demarcate the subtalar and talocrural axes, and markers were placed on these points. Marker clusters were also placed over the foot and leg. A 3-D kinematic data acquisition system was then used to record all marker motion during gait. During data analysis, the locations of the joint markers were used to mathematically define the axes of rotation from which the subjects' foot, ankle, and leg movement patterns were calculated. Throughout this process, Scott and Winter assumed that the subtalar and talocrural joints acted as polycentric hinge joints. The data they analyzed appeared to confirm these assumptions. As expected, some variability was found among subjects in terms of the measured joint angles of inclination. Variability was also noted with respect to the computed joint motion patterns. However, in a general sense, the kinematic data were well explained by this 2-joint model.

In 1994, van den Bogert et al[37] published a less subjective but more computationally intensive method for modeling the locations and inclinations of the talocrural and subtalar joints. With this protocol, 3-D kinematic data were captured while the subjects performed a series of wide-ranging foot and ankle movement patterns. Marker clusters were again used on the leg and foot. Calculations based on these body segment movements, however, were used to generate specific estimates of the internal geometry of the foot and ankle. In this study, this approach was applied with the purpose of conducting non–weight-bearing assessments of the subtalar joint. van den Bogert et al[37] do mention, however, that this technique could be used to conduct weight-bearing assessments if a device could be devised to permit each subject to remain in loaded contact over the various wide-ranging motion patterns. To their distinct credit, van den Bogert et al performed a detailed sensitivity analysis that demonstrated that their technique was capable of returning impressive accuracy. Surprisingly, although this model and the other more empirical approaches that preceded it[35,36] have all been academically appreciated, at present they do not appear to have been used in functional settings to examine clinical questions.

### Support from Radiographic Findings

In light of the efforts to capture 3-D data and develop advanced models to explain biomechanical function, recent attempts have also been made to radiographically quantify the structural characteristics of the foot and ankle. Fortunately, the information gained from these studies has played an important role in helping to reshape the scientific understanding of the mechanisms of foot orthotics. Nawoczenski et al,[2,22] for example, used detailed radiographic procedures to confirm the selection of subjects in their studies. They obtained both sagittal and anteroposterior radiographic views of the foot and ankle. Two specific angles, lateral calcaneal inclination and the lateral talometatarsal angle, were measured in the sagittal plane, whereas the anteroposterior talometatarsal angle was measured in the other view. Subjects were considered high-foot type if the 3 aforementioned angles were $\geq 25°$, $\geq 0°$, and $\geq 2°$, respectively. The 3 criterion angles for the low-foot type were 20°, $\geq -4°$, and $\geq -2°$, respectively.

Nawoczenski et al[2,22] assumed that the radiographic measures they had assessed were strongly predictive of the inclinations of the subjects' individual subtalar axes. Thus, McClay and Bray[38] conducted a study of 100 sagittal plane radiographs with the intention of characterizing the inclination of the subtalar axis. They chose to measure 4 specific landmarks on each of the radiographs. From these measurements, 4 sagittal plane angles were calculated. With respect to the estimates of subtalar inclination, the mean values ranged from 28.7° to 47.7°. These values appeared to be in good agreement with those that had been obtained from cadaveric studies.[31] Although good repeatability was also demonstrated ($r = 0.88$-$0.97$) in this report, McClay and Bray[38] concluded that the validity of their measures would require further testing with methods designed to measure subtalar inclination, such as those described previously.

Given the dual importance of the subtalar joint mechanism to convert planar motion and the stated intentions of orthotics to alter this mechanism, one would expect to find radiographic evidence documenting the ability of orthoses to alter bony alignment. In one radiographic study, Kuhn et al[39] found that the use of custom-designed flexible orthoses (Foot Levelers, Inc) produced significant improvements in pedal structure. In total, 22 subjects, each presenting with flexible pes planus, were recruited into the study. Radiographs were taken of the subjects' feet from 2 views as they stood in relaxed standing position, with and without the use of their orthoses. From these images, 2 radiographic angles were quantified with respect to the sagittal plane, whereas a third angle was measured from an anteroposterior view. Statistical analyses demonstrated that use of the orthoses produced a significant reduction in all 3 of the measured angles. On average, each angular measure was brought more in line with what would be expected for a normal foot. One peculiarity of this study was that, on viewing the anatomic figures of this article, one might actually have expected to see an increase in the 2 sagittal plane radiographic angles. A simple increase in arch height might have been expected since this particular orthosis is designed to fortify the 3 natural arches within the foot (medial longitudinal, lateral longitudinal, and transverse). Although Kuhn et al[39] did not actually comment on this phenomenon, it is suggested that use of the orthosis may have caused the foot to become more supinated. Increased supination about the subtalar joint would be an appropriate intervention for individuals with pes planus because excessive pronation is often considered a common problem in the low-arched foot.

### Alternative Mechanisms—Shock Absorption/Proprioceptive Enhancement

Although numerous research studies continue to examine the possible biomechanical/skeletal mechanisms of orthotic interventions, increasingly researchers are examining alternate mechanisms as a possible explanation for the success of foot orthoses. As Saltzman and Nawoczenski[40] have noted, the human foot is designed to provide load bearing, leverage, shock absorption, balance, and protection. Such diverse functionality involves the integration of complex neuromuscular and musculoskeletal systems. At present, the predominant orthotic paradigms have tended to focus on the latter, but it would seem that orthoses (or shoe inserts) could be easily used to alter virtually all facets of the human body's interface with the ground. Considered in this broader context, the design characteristics of an appropriate orthotic device grow considerably wider.

Altered shock transmission is perhaps the most conventional of the alternative orthotic mechanisms. In general, orthoses intended for this purpose have often been simplified in terms of their design and construction. For example, simple (flat) shoe inserts made of materials with increased viscoelastic properties (neoprene) have been found to reduce injuries.[41] In studies on the training of military recruits, even the use of basketball shoes rather than hard combat boots has been shown to be effective.[42] Great caution should be used when examining such studies, however, because the use of softer materials is not necessarily better. In the early 1990s, Robbins et al[43,44] led a well-documented crusade against trends that were then apparent within the athletic footwear industry. Robbins' studies showed that balance and proprioceptive performances were often impaired with the use of premium-priced shock-absorbing shoes that vendors had heavily marketed as being able to reduce injuries. In a series of research studies,[43,44] both young and old subjects actually demonstrated increased landing forces in response to the use of footwear with compressive qualities.[45] Therefore, Robbins and Gouw[46] hypothesized that humans must find it important to obtain a sufficient level of feedback through their feet. In this context, unconscious modifications in behavior to achieve such levels could actually result in an increase in injury rates. Although Robbins and his colleagues focused mostly on shoe construction, the use of over-the-counter orthoses or shoe inserts that are commonly marketed to soften impacts could also fall under this domain. Certainly, careful thought (and considerable research) must be given to the use of softer materials in footwear, because attempts to absorb impacts or modify vibrations may have surprising repercussions.

Recently, Nigg et al[7] proposed that proprioceptive enhancement may actually be the most important criteria in defining the success of orthotic applications. Lending greater sophistication to the simple shock absorption concept, they believe that advancements in understanding the tactile and proprioceptive needs of the human body could lead to careful tuning of the viscoelastic properties of shoes and shoe inserts. To this end, Nurse and Nigg[47] published an interesting study in which they measured unique patterns of pressure and vibration sensitivity across the plantar surface of the foot. With respect to pressure, the heel was found to be the least sensitive region of the foot, whereas the medial and lateral arches were the most sensitive. Two discrete frequencies, 30 Hz and 125 Hz, were used for the testing of vibration response. With the exception of the heel, greater sensitivity was found for the high frequency (125 Hz) input for all locations on the plantar surface of the foot. When considered in combination, these measurements also yielded another significant finding. Specifically, those subjects who possessed greater sensitivity under the hallux to the 125 Hz stimulation also demonstrated increased pressure measurements at this location during gait testing. These findings suggest that subjects who possess greater sensory feedback at this discrete location may make use of this ability by preferentially sharing the loads of the foot. Although Nurse and Nigg[47] did not test the effects of foot orthoses, it appears that such testing could have interesting implications. Presumably, the use of softer materials could reduce transference of the higher frequency vibrations from the ground up, thereby shifting the foot's perceived frequency content toward a less sensitive range. This could explain the subconscious reaction of Robbins' subjects to hit the ground harder.[43-46] Firmer materials with various viscoelastic properties might be used to enhance sensation, or perhaps different viscoelastic materials might be used at different regions under the foot to achieve customized neuromuscular responses. It should also be noted that the use of specialized materials (typically in simple shoe inserts) could be introduced to provide interesting effects when creating custom-fitted (casted) orthoses. It seems reasonable to consider that peak forces and rates of loading could be altered differentially as pressure is dispersed across the greater contact surfaces that a custom-fitted device provides.

One practical study that has provided a positive link between the use of foot orthoses and enhancements in balance performance and fatigue reduction is that by Stude and Brink.[48] They examined the effects of Foot Levelers orthotic devices on the static balance abilities of 12 experienced golfers while they participated in 9 holes of simulated golf. As noted in the study by Kuhn et al[39] described previously, these custom-fitted orthoses fortify the 3 major arches of the foot (medial longitudinal, lateral longitudinal, and transverse). Firm but flexible in design, these orthoses use materials of greater density in each arch support. The ramifications of this design seem particularly interesting, given that Nigg et al[7] found the medial and lateral arches to be the most pressure sensitive regions of the foot. In their study, Stude and Brink[48] noted a tendency toward improved balance scores with use of the orthoses over the length of the simulated golf match. The participants also showed a general increase in the symmetry of their balance scores with the use of orthoses. Large variability in the responses of one particular subject, however, prevented statistically significant results from being achieved. Still, Stude and Brink[48] concluded that enhancements in proprioception had been demonstrated in a majority of the subjects. In a follow-up study, Stude and Gullickson[49] reported on changes in golf performance for these same subjects. Although changes in swing accuracy were not measured, the use of the orthoses over a 6-week period was thought to result in a reduction of fatigue that permitted the golfers to gain a 7% mean increase in club-head velocity, as measured after 9 holes. These positive findings, along with those denoting improvements in pedal alignment,[39] suggest that the use of custom-fitted flexible orthoses can offer a range of benefits. Further research must be conducted to explore these effects.

Considered together, the present research findings appear to confirm and yet deny the commonly accepted theories with respect to foot and ankle assessment and orthotics practice. Routinely, clinicians perform static measurements of the lower extremity for the purposes of identifying pathologic characteristics of the foot. In attempts to confirm these findings, qualitative gait assessments are commonly performed, in which monitoring of rearfoot inversion/eversion motion is often considered the primary criterion. Surprisingly, the results of the previous studies indicate that the traditional static measurements used to classify foot type and orthopedic alignment actually have poor predictive value in estimating dynamic rearfoot function. Admittedly, the studies conducted by Hamill et al[12] and McPoil and Cornwall[13] evaluated young adult subjects, none of whom possessed obvious foot deformities. The fact that these individuals were judged, a priori, to have normal foot alignment meant that the static alignment measures of the subject groups, and perhaps even their dynamic rearfoot motion patterns, could be expected to demonstrate homogeneity. But in 2-D[14] and 3-D[22] studies that were purposely designed to examine variation in foot type, poor correlations were again found between static clinical assessments and rearfoot inversion/eversion measurements. It should be recognized that the advanced 3-D studies performed by Nawoczenski et al[22] and Stacoff et al[25] examined running rather than gait. The fact that inspection of these potentially more vigorous movements again returned no useful information with respect to inversion/eversion strongly suggests that the specific efforts by researchers and clinicians to examine frontal plane kinematics may in fact be misguided. The findings of advanced 3-D studies show quite clearly that simple planar analysis—the measurement of rearfoot motion (inversion/eversion)—is simply insufficient for the purposes of studying the biomechanical nuances of the foot and ankle during functional activities.

The findings of Nawoczenski et al[22] provide interesting implications for the revision of classic orthotics theory. Although true subtalar motion consists of uniaxial rotation around an obliquely directed axis, in practice the measurement of this motion is difficult to achieve. Conceptually, one must first correctly identify the 3-D orientation of the subtalar axis within the bones of the foot and ankle. The task of identifying the motion of the talus is particularly difficult because this bone sits deep within the ankle between the talocrural and subtalar joints. For these reasons, the clinical literature often uses the term *triplanar* to describe the subtalar joint's pronation/supination motion.[30] As such, subtalar pronation/supination is said to be composed of eversion/inversion in the frontal plane, medial/lateral rotation in the transverse plane, and a small amount of plantarflexion/dorsiflexion in the sagittal plane. In the study by Nawoczenski et al,[22] the high- arched individuals showed a greater range of medial/lateral rotation than the low-arched individuals, yet both groups produced similar ranges of motion in the other 2 planes (eversion/inversion, plantar/dorsiflexion). Thus, if one were to combine the findings from all 3 movement planes, it is actually the high-arched individuals who generated greater pronatory (and supinatory) movement patterns. Clearly, this interpretation appears to contradict the commonly held belief that low-arched individuals exhibit greater pronation as a result of their more flexible foot structure.[8,28]

We wish to offer further speculation on this apparent quandary between the clinical expectations of foot type and the foot's actual pronation characteristics. In the publications reviewed previously, Nawoczenski et al[22] chose only to present data that described the total ranges of rotation for the high- and low- foot types. We suggest that the presentation of data describing the mean and/or maximal angles of tibial rotation may have been highly informative. This suggestion is made for the following reasons. In their 2 articles, Nawoczenski et al[2,22] presented representative figures for 1 high-arched and 1 low-arched subject. On examining these figures, it appears that the tibial rotation range of the low-arched individual was significantly more medially rotated than was the high-arched subject. It also appears that the orthosis induced a wholesale lateral change in tibial rotation, thereby causing the low-arched individual to show a more neutral relationship throughout the stance phase. The data for the high-arched individual did not show such a change. Although such discrete responses should be interpreted cautiously, we suggest that if similar (averaged) findings were indeed noted across the subject groups, one could draw the conclusion that, although low-arched individuals generate less pronatory motion during running than their high-arched counterparts, they are generally more pronated (specifically, their tibia is more medially rotated) throughout this activity. Such an interpretation would clearly support the classic orthotics theory. Additionally, it would also confirm that orthotic interventions have the capacity to reduce the amount by which the foot and ankle are pronated—specifically, by reducing tibial medial rotation. Such an interpretation would also support the classic orthotics theory.

Such speculation on the work of Nawoczenski et al[22] compares favorably with the findings of Stacoff et al,[25] who reported that the use of orthoses produced a small yet significant reduction in the average maximal internal rotation of 5 subjects. They commented that considerable variability existed among the subjects, yet the individual orthopedic characteristics of the subjects (low, normal, high arch) were not actually presented. Based on the concepts described previously, perhaps those individuals in the study by Stacoff et al[25] who possessed a lower arch would be expected to exhibit a greater reduction in maximal tibial internal rotation. Presumably, a simple foot insert with a generic medial arch could have a reasonable influence on such subjects. Alternatively, it is possible that those with a high arch would have little if any contact with a generic insert and thus, little change in tibial rotation. This thought is tempered by the fact that arch supports were also tested under the sustentaculum tali; presumably, positive contact would be made at this location of the foot. Nevertheless, it seems reasonable to conclude that the choice of Stacoff et al[25] not to use custom-fitted orthoses essentially limited the effectiveness of their orthotics application.

Although traditional belief in the use of rigid or semirigid construction and/or the subtalar neutral position has been quite common, it appears that confidence in the use of other orthotic variants is increasing. As more knowledge is gained, there will be new opportunities for both patients and clinicians in the treatment of various foot, ankle, and skeletal alignment problems. Accordingly, peer-reviewed research should be performed to evaluate all such efforts.

### Increased Commercialization

Although many, if not all, of the authors mentioned here (and in a companion article[9]) have toiled long and hard in laboratories or clinics developing specialized skills and interests, it appears today that forces of commercialization are quickly overtaking the world of orthotics. In 1985, McPoil and Brocato[50] published detailed descriptions of the equipment required for the fabrication of orthoses. By 1994, Michaud,[30] in a chapter entitled, "Laboratory Preparation and Orthotic Fabrication," focused primarily on describing the casting techniques that clinicians need to know, suggesting that the fabrication of orthoses could be better done by commercial laboratories. At present, it seems reasonable to say that most new practitioners of orthotics (orthotists or pedorthotists excepted) are much more likely to use various commercial systems when treating their patients. Such decisions have had, and will continue to have, an impact on all phases of foot orthotics practice, from prescription to fabrication to fitting. Additionally, this trend toward commercialization will only increase, and interesting consequences can be expected to accompany this natural evolution.

First, although the early practitioner was required to have nearly complete knowledge (and financial investment) to use orthotics as a treatment modality, a clinician today has the potential to be much less involved. The decision now is generally about which product or commercial approach the clinician wishes to use, and the process through which the orthoses are created will tend to follow a specific formula. Although some control can still be exercised by the clinician regarding the type of orthoses (rigid, semi-rigid, flexible, or soft) that are created, the clinician essentially agrees to follow the procedures recommended by the manufacturer once a decision has been made to use a specific product.

Various manufacturers compete in the orthotics marketplace for the attention of clinicians and their patients. Perhaps not surprisingly, virtually all manufacturers state in their advertisements that they offer quality products that generate good clinical results. Nevertheless, because only a handful of commercial products[18,39,48] appear to have been tested in the peer-reviewed literature, one must assume that the claims made by a large majority of orthotics companies remain unsubstantiated. Indeed, in a recent issue of a popular health care trade magazine,[51] only 2 of 12 advertisements by foot orthotics manufacturers mentioned any form of "proof" for their claims, and neither indicated the details of their research. In truth, excellent research opportunities are now offered by the large volume of cases that are processed through commercial venues. Such issues make it incumbent on the commercial members of the orthotics industry to provide significant funding for research. In this way, the best interests of patients will continue to be met.

## Conclusion

Although the classic orthotics paradigm established primarily by Root and his colleagues still appears to dominate many fields of practice, the published research provides little support for the validity of these techniques from a mechanistic view. Fortunately, recent advances in 3-D measurement technologies are beginning to provide new opportunities to better appreciate the functional effects of orthoses. A key issue is the fact that measures of tibial internal/external rotation, rather than rearfoot inversion/eversion, provide a better indicator of foot and ankle function, particularly with respect to the discrete effects of foot type and orthotics use. Because of the unique ability of the subtalar joint to convert motion from the coronal into the transverse plane, great potential exists for research that uses advanced measuring and modeling techniques to better understand foot and ankle function. Such techniques may be used to explore theoretical and clinical questions regarding foot type (arch height), pathologic conditions, and the effects of orthoses on the motions of the foot, ankle, and lower extremities. We suspect that once such technical advances can be used in clinical research studies, clinical advances will be sure to follow. The creation of new or revised theoretical paradigms will be the end result.

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