The Influence of Two Different Types of Foot Orthoses on First Metatarsophalangeal Joint Kinematics During Gait in a Single Subject

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Abstract

Objective: To quantify the effect of two distinct foot orthotic designs on in vivo multisegment foot and leg motion; in particular, the first metatarsal and first metatarsophalangeal (MTP) joint during gait.

Methods: A 23-year-old man had an excessively pronated foot structure as measured during a clinical orthopedic examination. The Optotrak Motion Analysis System was used to collect three-dimensional position and orientation data from four modeled rigid body segments (hallux, first metatarsal, calcaneus, and tibia) during the stance phase of walking. The subject walked at a self-selected comfortable walking speed, and a minimum of five trials were collected under three different test conditions: no orthosis, semirigid orthosis with a varus post, and a semirigid orthosis with a varus post and a large medial flange. Data were normalized to the stance period, and descriptive statistics were calculated for dependent variables.

Results: Both orthotic interventions equally modified first MTP joint motion when compared with the no orthotic condition. First MTP joint dorsiflexion was decreased (>2 SD) with the orthosis during terminal stance phase. This decrease was associated with a concomitant increase in first metatarsal plantar flexion.

Conclusion: A custom-made semirigid orthosis posted medially and made from a neutral position off–weight-bearing plaster cast can alter motion in the forefoot during the propulsive period by increasing first metatarsal plantar flexion and decreasing excessive first MTP joint dorsiflexion. (J Manipulative Physiol Ther 2006;29:60-65)

Key Indexing Terms: *Orthotic Devices; Metatarsophalangeal Joint; Hallux Limitus*

The first metatarsophalangeal (MTP) joint consists of the first metatarsal head, the base of the proximal phalanx, the sesamoid groove, and the sesamoids. Its unique shape and complex blend of soft tissue–restraining mechanisms allow it to move through a large range of motion while simultaneously stabilizing the medial forefoot against the significant vertical and acceleration forces associated with the propulsive period of bipedal gait. Originally classified as a simple ginglymus joint,[1] the first MTP joint is now classified as ginglymoarthrodial or gliding hinge joint,[2] which is capable of transverse and sagittal plane motion.

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Because of technical difficulties associated with evaluating first MTP joint motion in vivo, several authors[1-4] have proposed a complex theoretical model of ideal first MTP joint motion that is summarized as follows: during the early stages of the propulsive period, the forward motion of the contralateral swing phase leg produces an external rotation of the ipsilateral weight-bearing femur (Fig 1, A), which creates a supinatory force at the subtalar joint by abducting the talus (Fig 1, B). Because the calcaneus is no longer maintained in a fixed position by ground contact, the entire rearfoot pivots medially as it abducts and dorsiflexes about the oblique midtarsal joint axis (Fig 1, C). This results is an increase in arch height as the foot moves into a low-gear push-off (Fig 1, black arrow). This increase in arch height is aided by muscles originating from the medial aspect of the calcaneus (particularly abductor hallucis) and by the Windlass mechanism of the plantar fascia; that is, dorsiflexion of the first MTP joint during the propulsive period creates a tensile strain that produces an approximation of the rearfoot and forefoot which in turn increases arch height.[5]

Because the first metatarsal is normally shorter than the second metatarsal, it must actively plantar flex to maintain ground contact during the propulsive period (Fig 2, A). As the first metatarsal plantar flexes, its metatarsal head glides posterior along the sesamoids (Fig 2, B), which in turn

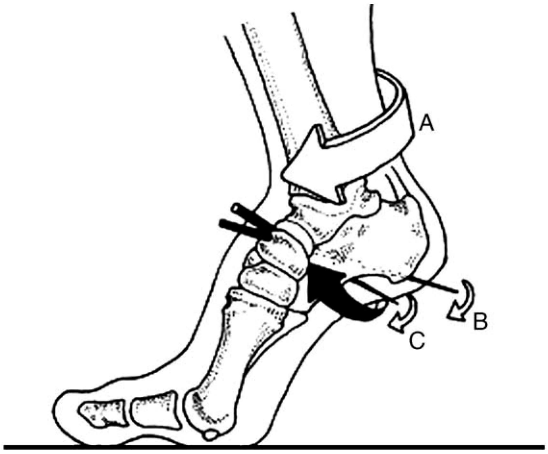

Fig 1. *Articular interactions present during early propulsion (see text for discussion). Reproduced with permission from Michaud.*[3]

allows for a dorsal-posterior shift of the transverse axis of the first MTP joint (Fig 2, C). This new axis allows for an unrestrained range of hallux dorsiflexion and improved congruency between the distal first metatarsal head and its proximal phalanx (Fig 2, D).

This theoretical model of ideal first MTP joint motion depends on the first metatarsal actively plantar-flexing during the propulsive period. Failure of the first metatarsal to plantar-flex during propulsion (Fig 2, E) inhibits the normal posterior glide of the metatarsal head on its sesamoid (Fig 2, F), thereby preventing the dorsal-posterior shift in the transverse axis (Fig 2, G). The hallux is now forced to dorsiflex about the original axis, which results in a decreased parallelism of the articular surfaces with resultant jamming of the dorsal cartilage (Fig 2, H). This limitation in motion in the first MTP joint secondary to faulty biomechanics (ie, the range of motion in the first MTP joint is limited during weight-bearing examination but is unaffected during off–weight-bearing examination) has been referred to as a functional hallux limitus.[2-4]

Contrary to the aforementioned first MTP joint pathomechanics, recent investigations of forefoot and rearfoot coupling using multisegment foot models have challenged the conventional theories regarding limitation of hallux motion during gait. Rather, excessive hallux dorsiflexion motion has been described in the abnormally pronated, young adult foot during gait.[6] Because foot orthoses have the potential to minimize abnormal rearfoot and midfoot pronation during stance,[7] related positive changes should also be seen in first metatarsal plantar flexion and hallux dorsiflexion during the propulsive period of gait. To date, there has been little scientific evidence to verify the forefoot changes imposed by distinct orthotic designs advocated for treatment of abnormal pronation.

The purpose of this study was to evaluate the effect of two different orthoses on the kinematic coupling between the rearfoot and the first metatarsal/first MTP joint during gait in an individual who presented clinically with an excessively pronated foot structure. We hypothesized that orthotic intervention would increase the range of first MET plantar flexion and minimize abnormal motion of the first MTP joint during the propulsive period of gait. We anticipated that the orthotic intervention manufactured with the large medial flange would be the most effective design in altering the joint kinematics as it projects significantly farther up the medial aspect of the arch, theoretically providing additional support to the midfoot.

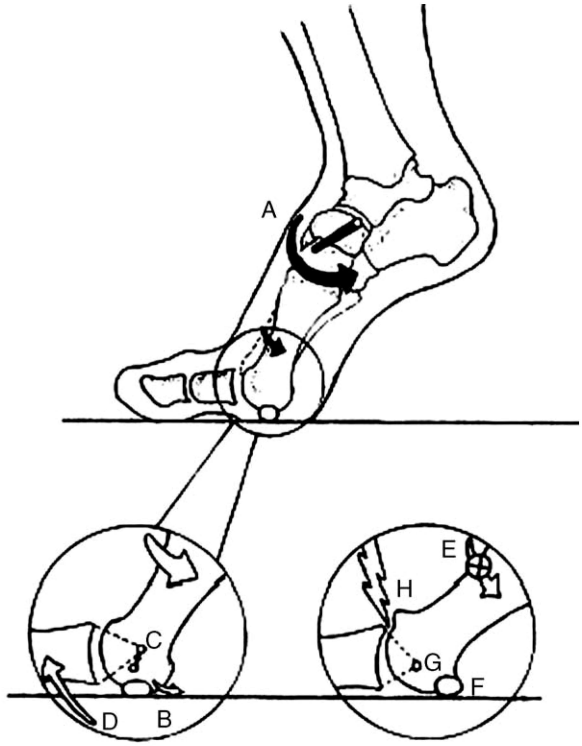

Fig 2. *Theorized MTP joint interactions. Reproduced with permission from Michaud.*[3]

Methods

Subject

The subject was a 23-year-old man (weight, 90 kg; height, 1.93 m) who presented with a history of musculoskeletal symptoms in his right lower extremity, including medial tibial stress syndrome, plantar fasciitis, and the presentation of a "pes planus" foot. This individual was part of a larger investigation of abnormal foot structures[8] and met the clinical criteria of abnormal pronation for the study[9-12] that included a forefoot varus exceeding 10° in the non–weight-bearing examination, calcaneal eversion beyond vertical while standing, a navicular drop greater than 10 mm between subtalar neutral and relaxed stance, and no limitations of hallux motion (ie, the patient's range of off-weight bearing first MTP joint dorsiflexion was 115° bilaterally). Observational gait evaluation revealed excessive subtalar joint pronation during the contact period along with a complete collapse of the medial longitudinal arch throughout the stance phase of gait. This individual was considered an appropriate candidate for orthotic intervention based on his history of lower extremity musculoskeletal symptoms and findings from the clinical screening examination. The participant read and signed an informed consent document approved by the Human Subjects Review Board at Ithaca College. Testing took place at the Movement Analysis Laboratory at Ithaca College–University of Rochester campus facility.

Materials

A single examiner (T.C.M.) with 22 years of clinical experience took the slipper cast impressions in the non–weight-bearing position. The talonavicular joint was maintained in its neutral position, and the lateral column was locked by applying a dorsiflexion force to the fourth and fifth metatarsal heads. Two pairs of orthoses were made from these impressions. Before molding the orthoses, the laboratory (Allied Orthotics, Inc, Londonderry, NH) was instructed to avoid lowering the medial longitudinal arch while fabricating the positive model (normally, the laboratory will modify the positive model by adding 1/4 inch of plaster to the arch area, thereby allowing for deflection of the midtarsal joint during stance phase). It was theorized that the higher arch associated with this modification would provide greater support to the midfoot, thereby allowing for increased first ray plantar flexion during terminal stance phase. The shell of the orthoses was made from 5/32-in polyethylene and was posted extrinsically with styrene butadiene rubber (40 durometer) with a 4° varus angle in the rearfoot and a flat forefoot post (also posted extrinsically with styrene butadiene). A vinyl top cover with a 1/8-inch poron extension projected to the sulcus was added for comfort. A second pair of orthoses was made from the same positive model with the same shell and post angles; only this pair was made with a large medial flange projecting superomedially to the navicular tuberosity. Deep heel cups were also added to both orthoses. For the purposes of this study, kinematic analysis was conducted for the symptomatic extremity.

Instrumentation

The Optotrak Motion Analysis System was used to track three-dimensional position and orientation of the hallux, first metatarsal, calcaneal, and tibial segments during walking. A stylus with known tip offsets from the sensor was used to manually digitize anatomical landmarks on each segment. Previous cadaveric studies in our laboratory have shown high reliability and validity of surface sensors to detect underlying bony movement over the first metatarsal and proximal hallux segments.[13] Data were sampled at a rate of 100 Hz.

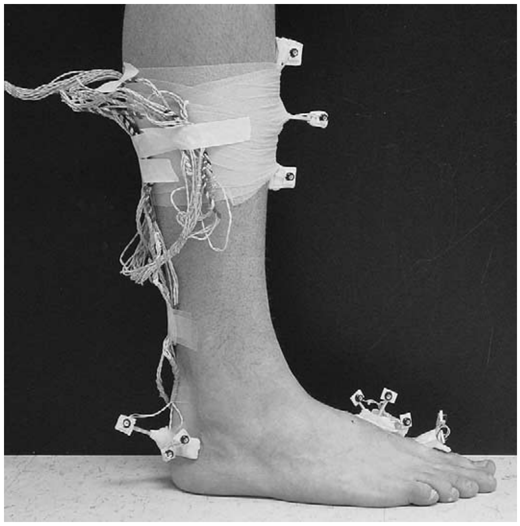

Fig 3. *Sensors for the Optotrak Motion Analysis System.*

Procedure

Infrared sensors, mounted on rigid body platforms, were placed on the skin overlying the proximal hallux, first metatarsal, lateral calcaneus, and anterior tibia (Fig 3). Anatomical bony landmark data were collected with the subject standing in a relaxed stance posture with a comfortable base of support. The bony landmark data allow for subsequent transformation of the sensor data to local, anatomically based coordinate systems defined in each rigid body segment. The testing order for each orthotic condition was randomized with a minimum of five trials collected for each orthotic condition. Data were collected while the subject walked at a self-selected pace over a 10-m walkway with the orthotics secured to each foot via a soft slipper. Walking speeds were maintained within ±5% across conditions and monitored by speed traps at preset locations on the walkway.

Data Reduction and Analysis

Local orthogonal coordinate systems were defined for each rigid body segment such that the positive z-axis was directed approximately lateral, the positive x-axis directed anteriorly within the long axis of the segment, and the positive y-axis directed approximately superior. The anatomical landmarks and coordinate systems have been described in previous investigations.[14,15] Transformation matrices related the assumed constant orientation of the sensors to the local anatomical coordinate systems. A Cardan system of three orders of rotations (Z-Y′-X″) was used to extract angular and linear information of the hallux

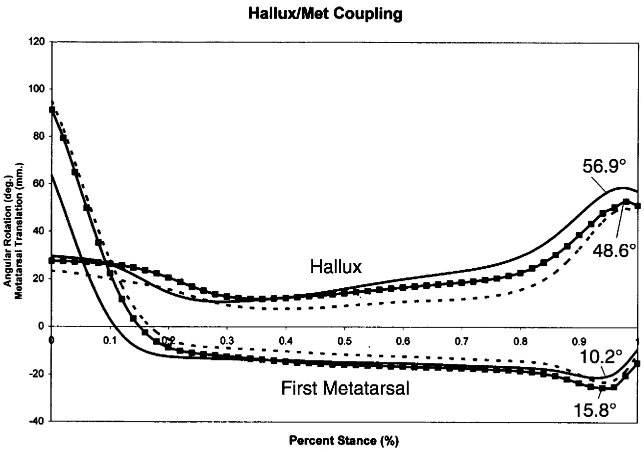

Fig 4. *Hallux/first metatarsal coupling. Straight line indicates no orthotic; dashed line, standard orthotic; boxed line, orthotic with high medial flange. Positive numbers indicate dorsiflexion; negative numbers, plantar flexion.*

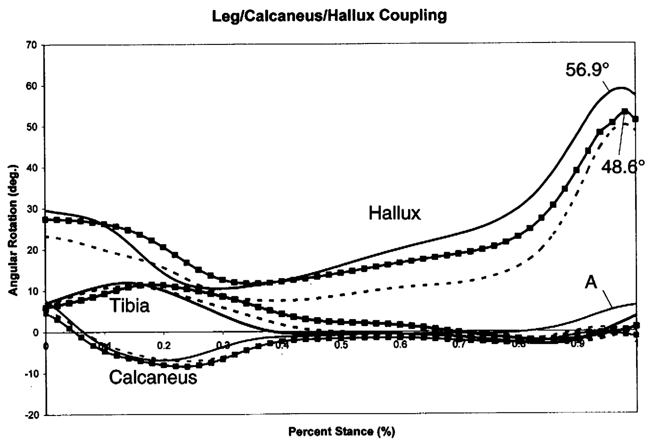

Fig 5. *Leg/calcaneus/hallux coupling. Straight line indicates no orthotic; dashed line, standard orthotic; boxed line, orthotic with high medial flange. Positive numbers indicate dorsiflexion, internal rotation, and inversion; negative numbers, plantar flexion, external rotation, and eversion for the hallux, tibia, and calcaneus, respectively.*

with respect to the first metatarsal, first metatarsal translation of the origin point on the distal metatarsal head with respect to the laboratory (or global) coordinate system, and calcaneal motion with respect to the distal leg and tibial rotation with respect to the foot. The laboratory reference frame was aligned with the x-axis directed positive/anterior and in the horizontal plane and the y-axis directed vertically upward. Although data are presented for the calcaneal eversion and inversion and tibial internal and external rotations, the primary focus of this case study is directed to the clinically relevant rotations describing dorsiflexion/plantar flexion at the first MTP joint and first metatarsal translation, also described as dorsiflexion/plantar flexion during the propulsive period of the gait cycle.

For each orthotic condition and each trial, data were normalized to 100% of stance to enable comparisons across conditions. Mean (five trials) and SD values were determined for the dependent variables of interest. A minimum 2 SD criterion was used to operationally define significant differences between conditions.

Results

Mean and SD values for peak rotations and metatarsal translation occurring during stance phase are illustrated in Fig 4. Both orthotic conditions resulted in a favorable response of increased metatarsal plantar flexion during the terminal stance compared with the no orthotic condition. Associated with this increased metatarsal plantar flexion was a significant reduction in first MTP dorsiflexion when compared with the no orthotic condition. Although there was essentially no difference between the two types of orthotics, both altered motion during terminal stance compared with the no orthotic condition.

Continuous data for the kinematic interactions that occurred for tibial rotation, calcaneal inversion/eversion, and first MTP dorsiflexion/plantar flexion across conditions are illustrated in Fig 5. Generally speaking, there was a clear decrease in first MTP dorsiflexion associated with orthotic use (both with and without the medial flange), but there was also an increase in calcaneal inversion during terminal stance in the no orthotic condition (Fig 5, A). This finding is somewhat surprising as one would expect the no orthotic condition to be associated with increased calcaneal eversion (ie, greater rearfoot pronation).

Discussion

Numerous investigators have demonstrated variability in individual subject response to orthotic use.[16,17] The previously held belief that orthotic intervention lessens rearfoot pronation, thereby providing for an increased range of first MTP joint dorsiflexion during the propulsive period, needs to be reevaluated. The fact that excessive pronation does not produce a locking of the first MTP joint was conclusively demonstrated in the young adult foot by Nawoczenski et al.[6] Using the same methods as described in this study, first MTP joint and first metatarsal kinematics were evaluated in 11 neutral foot types and 17 abnormally pronated foot types. The investigators noted significant differences between the two groups in the magnitude of first MTP joint kinematics: the pronator group moved through an average of 55° first MTP dorsiflexion during the propulsive period (SEM, ±1.4°) while the neutral group moved through a 49° range of dorsiflexion (SEM, ±1.3°). The 55° range of dorsiflexion found in the pronators was almost identical to the 56° range of dorsiflexion found in our subject pretreatment. The difference in first MTP joint dorsiflexion in neutral and pronated foot types is most likely due to excessive or prolonged pronation that results in an inability to generate adequate supinatory moments during the propulsive phase of gait.[18] This almost certainly results in a greater force being centered beneath the hallux, which forces the first MTP joint into a more dorsiflexed position. We believe that this increase in first MTP joint dorsiflexion may predispose the joint to subsequent arthritic changes, later seen in the older adult foot as hallux limitus and rigidus. Restoration of "normal" motion therefore would be a desirable goal.

The belief that lessening first MTP joint dorsiflexion may be of value in the treatment of hallux limitus is supported by several cadaveric studies. Shereff et al[19] evaluated first MTP joint motion in 15 fresh-frozen below-the-knee amputations, six of which were normal, six had hallux abductovalgus, and three had hallux limitus. Motion analysis of the normal MTP joints revealed a "tangential sliding" of the proximal phalanx on the metatarsal head from maximum plantar flexion to moderate dorsiflexion with "compression" of the joint surfaces occurring at maximum dorsiflexion. In a more recent study, Heller and Brage[20] used radiographs to evaluate first MTP joint dorsiflexion in 10 fresh-frozen cadaveric feet possessing hallux limitus. Using a custom-made tray with a special hinge mechanism to dorsiflex the first MTP joint, lateral radiographs were taken at neutral, 20°, 40°, and at the limit of the available dorsiflexion. Results revealed that, in the hallux limitus population, a normal "sliding" motion predominated in the initial stages of dorsiflexion, but as the MTP joint reached its end range of motion, there was an increase in compressive forces that produced a "jamming of the articular surfaces." It is theorized that, by allowing the individual with hallux limitus to avoid the final range of first MTP joint dorsiflexion, orthoses may help to minimize compressive forces present during terminal dorsiflexion.

The findings of this study also provide a possible explanation for the efficacy of orthotic intervention in the treatment of plantar fasciitis. Because the medial band of the plantar fascia attaches to the base of the proximal phalanx, an orthotic that decreases first MTP joint dorsiflexion while simultaneously increasing first metatarsal plantar flexion could significantly lessen strain on the plantar fascia by decreasing the tensile stress placed on this tissue during the propulsive period. The connection between plantar fascia tension and first MTP joint dorsiflexion was recently demonstrated in a study by Harton et al.[21] These researchers noted that, when the medial band of the plantar fascia was surgically sectioned for the treatment of recalcitrant plantar fasciitis, there was an immediate 9.8° increase in first MTP joint dorsiflexion (the sample group consisted of 18 patients with chronic plantar fasciitis who had no first MTP joint pathology). Another interesting study supporting this hypothesis was published by Katoh et al.[22] These researchers divided heel pain patients by diagnoses into plantar fasciitis and infracalcaneal bursitis groups and had them walk on the force platform. Surprisingly, the bursitis patients shifted weight to the forefoot, but the plantar fasciitis patients paradoxically shifted weight toward the painful heels. It is conceivable that the plantar fasciitis patients did this in an attempt to decrease forces centered beneath the hallux, thereby lessening first MTP joint dorsiflexion. Additional research is needed to compare force plate data with kinematic data.

It was surprising to note that the reduction in first MTP joint dorsiflexion found in this study occurred without simultaneous inversion of the calcaneus; there was only a slight change in frontal plane calcaneal position with or without different orthoses. This is in contrast to a prior static study linking rearfoot eversion with functional hallux limitus as Harradine and Bevan[22] demonstrated that hallux dorsiflexion decreased as rearfoot eversion increased in a static setting. It is likely that after heel lift occurs, the clinically most significant motions occur in the transverse and sagittal planes of the midfoot, which may not be linked to frontal plane rearfoot motion.

Limitations of the Experimental Model

As this was a single subject design, a larger scale version of this study is suggested. A possible problem with the protocol used in this study is that the patient may have felt unstable while walking with the orthotic strapped to his foot. This may have resulted in a reduction in his stride length, which may have led to a corresponding decrease in his range of first MTP joint dorsiflexion. Subjectively, this was not reported as the patient claimed that the orthotic was comfortable and that it did not alter his walking pattern. This is also supported by the kinematic data showing identical ranges of ankle dorsiflexion just before heel lift with and without the orthotic. If his stride length was shortened by orthotic intervention, there would have been a corresponding reduction in ankle dorsiflexion.

Further research is suggested to evaluate kinematic differences among different patient populations (normal, hypopronaters, and hyperpronaters) to see if certain foot types respond differently to orthotic intervention. It would also be interesting to see if different types of orthotics (eg, hard vs soft) and/or if different casting techniques (off-weight bearing vs weight bearing) affect the kinematic outcomes. We chose a semirigid orthotic made from an off-weight–bearing cast as the semirigid orthotics have demonstrated better effectiveness in controlling motion during the propulsive period,[23] whereas an off-weight–bearing neutral position plaster cast captures a picture of the foot with the medial longitudinal arch elevated compared with its weight-bearing position.[3] A high arch on an orthotic may simply force the foot into a more supinated position, thereby decreasing pressure centered beneath the hallux during terminal propulsion.

Conclusion

Taking into consideration that this was a case report, this investigation offers interesting insight regarding in vivo function of the first MTP joint with and without orthotics. A semirigid orthotic with a rearfoot varus post made from a neutral position off–weight-bearing cast, with or without the incorporation of the medial flange, modified motion by decreasing first MTP joint dorsiflexion and increasing first metatarsal plantar flexion during the propulsive period of the gait cycle. This may play a role in managing first MTP joint pain in the early stages of arthritis of the first MTP joint frequently associated with hallux limitus deformity.

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