Effect of Functional Foot Orthoses on First Metatarsophalangeal Joint Dorsiflexion in Stance and Gait

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Reduction in first metatarsophalangeal joint maximum degree of dorsiflexion with dorsiflexion of the first ray has been proposed to be the predominant cause of hallux abducto valgus and hallux rigidus. We sought to determine whether orthoses made from a cast with the first ray plantarflexed and a 4-mm medial skive could increase the maximum degree of dorsiflexion in patients with functional hallux limitus in stance and gait. Forty-eight feet of 27 subjects were casted for orthoses with the first ray plantarflexed and in the customary neutral rearfoot position with locked midtarsal joint. First metatarsophalangeal joint maximum dorsiflexion was measured with and without orthoses in stance, and subhallux pressure was measured with and without orthoses at heel-off. Changes in mean maximum dorsiflexion in stance and in mean maximum subhallux pressure in gait with orthoses were significant. We investigated the relationship between this increase in dorsiflexion and gender, shoe size, resting calcaneal stance position, and change in resting calcaneal stance position with the use of orthoses. These correlations were not statistically significant. The biomechanical implication of increasing limited first metatarsophalangeal joint dorsiflexion with orthoses is discussed and related to the clinical treatment of deformities, including hallux valgus and hallux rigidus. The use of orthoses to decrease subhallux pressure is also discussed. (J Am Podiatr Med Assoc 96(6): 474-481, 2006)

Sagittal plane motion of the first metatarsophalangeal joint is an essential component of the normal function of the human foot during gait. Dorsiflexion at this joint in gait is mandated by heel-off. This dorsiflexion motion may depend on the position of the first metatarsal in relation to the rest of the foot. Pathology such as functional hallux limitus and deformities such as hallux valgus and hallux rigidus have been proposed to develop from dysfunction of this joint, secondary to malposition of the first ray in the sagittal plane.[1] We suggest that repositioning the first ray with the use of a functional foot orthosis, fabricated from a negative cast with the first ray plantarflexed and a 4-mm medial skive, will increase

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the maximum degree of dorsiflexion of the first metatarsophalangeal joint, providing further evidence that orthoses can help relieve symptoms related to functional hallux limitus.

A previous study[1] showed that when the first ray was artificially dorsiflexed in stance, first metatarsophalangeal joint motion decreased an average of 19.3%. The purpose of this study was to determine whether use of a contoured semirigid functional orthosis made from a negative cast with a plantarflexed first ray and a 4-mm medial skive would increase the maximum dorsiflexion of the first metatarsophalangeal joint. Such an increase in the maximum degree of dorsiflexion can be measured in gait as a decrease in subhallux pressure after heel-off.

Review of the Literature

The quest for an understanding of the relationship between foot position and first metatarsophalangeal joint motion has continued since 1905, when Hoffman[2] completed a comparative study of shod and unshod feet. He suggested not only that shoes produced foot pathology but also that foot position or abnormal motion might produce first metatarsophalangeal joint dysfunction. A later pair of articles[3, 4] supported the idea that abnormal mechanics of the foot might be related to dysfunction of the first metatarsophalangeal joint that resulted in pathology, including hallux valgus.

Hicks[5] found that the distance between the origin and the insertion of the plantar aponeurosis was shortened with hallux dorsiflexion and that "the arch was thereby made shorter and higher." This became known as the windlass effect of Hicks. He proposed that the mechanism would work in reverse: If the arch of the foot was lowered, the windlass would unwind and decrease the ability of the hallux to dorsiflex. No converse proposal was made to suggest that again raising the arch, or the base of the first metatarsal, would release this restriction and increase hallux dorsiflexion.

Restriction of first metatarsophalangeal joint dorsiflexion, called hallux limitus, is reported in several articles[6-8] to produce abnormal foot function. Abnormal first metatarsal position was later reported to restrict first metatarsophalangeal joint dorsiflexion.[1] That article describes a progressive restriction of first metatarsophalangeal joint dorsiflexion when the first ray is artificially dorsiflexed.

Several authors[9, 10] have previously shown that a change in the position of the foot using varus or valgus wedges can increase hallux dorsiflexion. One study[11] investigated the effect of modified Root orthoses on maximum hallux dorsiflexion. It showed a decrease in first metatarsophalangeal joint motion when the foot was shod but no increase or decrease when the orthotic device was inserted into the shoe. A similar study[12] investigated the negative effect of valgus insole wedging on maximum hallux dorsiflexion in static stance. The study tested 44 feet and measured weightbearing hallux dorsiflexion with a 3°, 5°, and 8° valgus wedge. The study concluded that a 3° valgus wedge limited dorsiflexion of the hallux by placing the rearfoot in a pronated position. Larger wedges of 5° and 8° did not create additional motion restriction.

A further study[13] attempted to use custom and noncustom orthoses to increase hallux dorsiflexion as determined by a reduction in symptoms in 30 patients with hallux limitus. Neither the custom nor the prefabricated orthoses produced a significant change in symptoms. Finally, a recent study[14] identified first metatarsophalangeal joint dorsiflexion as a distinct pronation-sensitive attribute of the weightbearing foot. The authors applied a low-Dye strap to determine whether limiting pronation in stance increased the range of dorsiflexion. They found that the antipronatory strapping increased the range of dorsiflexion of the first metatarsophalangeal joint.

Functional Hallux Limitus

Functional hallux limitus has been described as the inability of the first metatarsophalangeal joint to dorsiflex sufficiently during gait when normal motion is present on nonweightbearing examination.[15] The first use of the term *functional hallux limitus* in the podiatric medical literature was by Laird[16] in 1972, when restriction of first metatarsophalangeal joint motion was suggested to originate from mechanical factors rather than structural abnormalities. That study defined functional hallux limitus as a pathologic entity presenting as first metatarsophalangeal joint motion greater than 50° during nonweightbearing but less than 14° during weightbearing. The hallux must continue to dorsiflex to accommodate the concomitant heel-off (Fig. 1). Forced dorsiflexion of the hallux during continued heel-off, in the presence of functional hallux limitus, must produce abnormal and pathologic forces in the first metatarsophalangeal joint. For the purposes of this article, we define freedom of motion of the first metatarsophalangeal joint as sufficient dorsiflexion to accommodate heel-off.

The decrease in motion called functional hallux limitus has been attributed, in the literature, to heredity,[17] osteoarthritis,[18, 19] osteochondritis dissecans,[20, 21] avascular necrosis,[22] and congenital fragmentation of the epiphysis in the base of the proximal phalanx of
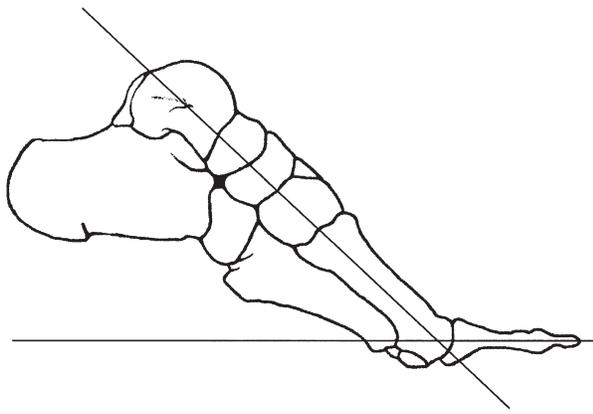
Figure 1. An uninhibited first metatarsophalangeal joint must have sufficient freedom of motion to accommodate heel-off in gait.

the hallux.[23] Although each of these pathologic entities may contribute to the limitation of hallux dorsiflexion, we contend that a pathomechanical event occurs, with abnormal dorsiflexion of the first ray that limits first metatarsophalangeal joint motion, when full range of motion is available. This concept is not new, as the position of the first ray has been inferred in the literature to affect the motion of the first metatarsophalangeal joint.[24, 25] Both articles suggest that a "hypermobile" first ray produces abnormal motion at the first metatarsophalangeal joint.

Several additional authors[18, 22, 26] suspected that either a change in the instant center of rotation or an anatomical variation in the instant center of rotation causes restriction of dorsiflexion of the hallux. None, however, speculate as to why or how to deliberately alter the instant center of rotation and reverse the restriction to increase the range of motion.

Rather than considering anatomical or proximal functional variations, we believe that the motion of the first metatarsophalangeal joint is governed primarily by the position of the first ray. The purpose of this study was to determine whether artificial plantarflexion of the first ray can increase first metatarsophalangeal joint dorsiflexion and whether this effect can be produced with a functional foot orthosis. The null hypothesis was that a functional foot orthosis does not affect first metatarsophalangeal joint dorsiflexion.

Materials and Methods

Two separate experiments were performed on the same group of subjects, one for stance and one for gait. Subjects in both studies were required to meet the following conditions: 1) no history of trauma to

the foot, 2) the presence of at least 10° of dorsiflexion at the ankle with the knee fully dorsiflexed, 3) unrestricted motion of the functional subtalar joint of 30°, 4) unrestricted motion at the longitudinal axis of the midtarsal joint of 15°, 5) unrestricted nonweightbearing motion of the first ray of at least 8 mm, 6) greater than 50° of dorsiflexion of the hallux to the first metatarsal bisection during nonweightbearing and less than 12° of dorsiflexion during weightbearing, and 7) older than 21 years and younger than 60 years. At the time of data collection, there was no institutional review board at the institution.

Students, nurses, residents, and physicians were recruited by flyer. Forty subjects responded, and 27 attended initial screening. Twenty-seven subjects (11 men and 16 women) and 48 feet met the study criteria for stance measurement. The gait segment of the experiment was performed with 18 subjects and 33 feet from the previous study group. The remainder of subjects not tested were no longer available for follow-up or did not continue to meet the original criteria. Nine subjects were lost to follow-up because of change in location (n = 5), change in employment (n = 1), trauma to the joint (n = 1), or nonresponse to communication (n = 2). The qualifying joint ranges of motion were measured as described by Root et al[27] by the same experienced examiner (D.E.E.) on the same day. Each measurement was performed three times, and the mean of the measurements was used for the data. The resting calcaneal stance position was measured, and the skin on the back of the weightbearing heel was marked with a bisector perpendicular to the floor. This indicator was used to determine any resulting inversion or eversion of the heel with and without the orthoses.

Functional foot orthoses were fabricated from milled semirigid polypropylene using a Root-method[28] neutral-position nonweightbearing cast that was balanced to perpendicular and with the first metatarsal intentionally plantarflexed by dorsiflexion of the first metatarsophalangeal joint (Fig. 2). The same clinician (P.R.S.) using the same method performed all of the casting. Each orthosis was made from $^3/_{16}$-inch vacuum-formed polypropylene with minimum fill positive, 14-mm heel cup, 4-mm medial skive technique,[29] wide width, and a 4/4 rearfoot polypropylene post consistent with Prescription Foot Orthotic Laboratory Association guidelines.[30]

Subjects were instructed, before negative casting, to stand in the angle and base of gait with the hallux perpendicular to the hinge axis on the weightbearing goniometer. This was considered to represent the weightbearing resting position of the first ray. The distal segment of the goniometer was then dorsi-

Figure 2. The first metatarsal was intentionally plantarflexed while the subtalar joint was held in the neutral position and the midtarsal joint was fully pronated by dorsiflexing the forefoot on the rearfoot.

flexed perpendicular to the joint axis until resistance was felt and frontal plane motion was noticed to begin in the rearfoot as a result of the windlass mechanism (Fig. 3). This point was easily discriminated within 1° by the same examiner. This was considered to represent the maximum degree of dorsiflexion of the first metatarsophalangeal joint.


Figure 3. While the patient stood in the angle and base of gait, the hallux was dorsiflexed until resistance was felt and motion was noticed in the rearfoot as a result of the windlass mechanism with and without orthoses.

The functional orthosis, previously described, made from the negative cast with the first ray plantarflexed was placed on the goniometer, and the patient was placed in the same position. The maximum degree of dorsiflexion of the first metatarsophalangeal joint was again tested by dorsiflexing the hallux to resistance and the point at which rearfoot motion began. Changes in motion were recorded to the nearest degree. The bisection of the calcaneus was photographically recorded with and without the orthoses, and a degree of verticality to the ground (inverted/everted) was recorded. The change in the degree was calculated and compared with the resulting change in the maximum degree of dorsiflexion.

The second phase of the study involved recording the subhallux maximum pressure in gait using an in-shoe recording instrument (F-Scan; Tekscan, Boston, Massachusetts) at the beginning of heel-off until toe-off. Each subject was fitted with an Addiction Walker shoe (Brooks Sports, Bothell, Washington) by existing shoe size. The same orthosis from the stance trial was placed in the shoe, and the F-Scan in-shoe sensor was placed on top of the orthosis, extending heel to toe, before the subject's foot was again inserted into the shoe. The subjects had worn the orthoses daily for a minimum of 3 weeks, in their own shoes, before this part of the test. Each subject spent several minutes in the shoes, and then a six-step gait cycle was recorded through a tether connection on a thinly carpeted concrete floor. The first and last steps were eliminated from the data, and the average maximum hallux pressure from heel-off to toe-off was calculated for the remaining four steps.

An assumption was made in the gait study that heel-off creates compensatory dorsiflexion of the first metatarsophalangeal joint if sufficient freedom of motion is available. Deficient freedom of motion caused by functional hallux limitus at heel-off would create a proportional increase in pressure under the hallux. Recording and comparing the decreased hallux pressure at heel-off with and without the orthoses would represent a quantitative change in the freedom of motion of the first metatarsophalangeal joint.

Data collected in the first study included the mean degrees of maximum dorsiflexion in stance without an orthosis, the same measurement with an orthosis, and the percent change. Data collected in the second study included the mean maximum pressure per square inch under the hallux without an orthosis and the same measurement with an orthosis. A digital mask was created under each individual's subhallux pressure graphic surrounding all of the pressure marks made by the hallux (Fig. 4). Relationships with gender, shoe size, resting calcaneal stance position,
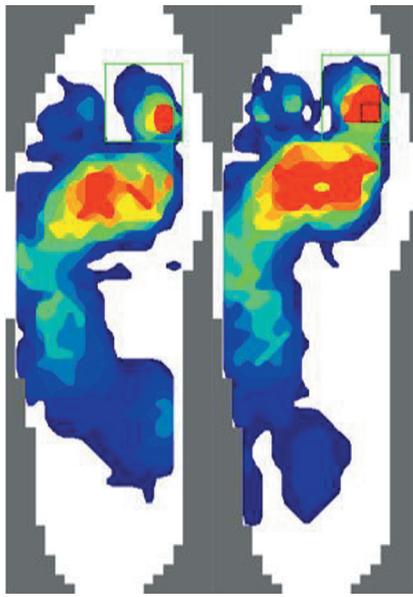
Figure 4. F-Scan software (version 5.26) was used to analyze the pressure data. Virtual boxes were defined, allowing the user to monitor the pressure under the hallux exclusively. The size of the box was dictated by the size of the subject's hallux. Once a box size was deemed appropriate for a subject, it was standardized within all of the conditions for that subject. The magnitude of peak pressure was identified by inspecting the changes in the peak pressure time series.

and change in resting calcaneal stance position were investigated to determine their effect on the results.

A university-associated consultant provided statistical analysis. The mean (SD) maximum dorsiflexion with and without orthoses was calculated. The mean (SD) increase was calculated, and the *t* test was used to determine statistical significance, with the significance level set at $P < .001$. Correlations of increased dorsiflexion to the subject's weight, shoe size, and gender were calculated. To examine how the difference between nonweightbearing and weightbearing range of motion affects the increase in dorsiflexion with an orthosis, a Spearman rank correlation was performed. Similarly, the effect of resting calcaneal stance position on dorsiflexion was measured. A change in an individual subject's resting calcaneal stance position from 2° everted to 3° inverted, for example, represents a change of 5°.

Results

The stance segment of the experiment was performed with 27 subjects (11 men and 16 women) and 48 feet.

The average weight of the subjects was 167 pounds (range, 105–285 pounds). The average shoe size was 7½ for women and 10½ for men. The largest shoe size was a men's 12½; the smallest shoe size was a women's 6½. The resting calcaneal stance positions recorded for the subjects were inverted in five feet, perpendicular in four, and everted in 39. Average heel eversion was 5.6°.

The nonweightbearing examination of first metatarsophalangeal joint motion demonstrated mean dorsiflexion of 75.7° (range, 50°–105°). The weightbearing examination of first metatarsophalangeal joint motion demonstrated mean ± SD dorsiflexion of 9.8° ± 2.64° (range, 4°–14°). Adding the orthoses to the stance segment of the experiment increased the mean ± SD maximum degree of dorsiflexion to 18.61° ± 3.37° (range, 12°–28°). This represents a mean increase of 8.81° or 90%. The increase in motion with orthoses is significant ($P < .001$). All of the subjects in the stance experiment had an increase in their maximum degree of dorsiflexion (Fig. 5).

The mean ± SD maximum subhallux pressure in gait without orthoses was 127.85 ± 29.15 kPa (range, 62.5–192.5 kPa). Adding the orthoses to the shoe reduced the mean ± SD maximum subhallux pressure to 108.93 ± 30.12 kPa (range, 57.4–186.3 kPa). This represented a 14.8% reduction in pressure. The decrease in pressure with the orthoses is significant ($P < .001$). The greatest subhallux pressure reduction was from 146.1 to 74.5 kPa, a 49% decrease. The smallest subhallux pressure reduction was from 121.6 to 119.2 kPa, a 2% decrease. All of the subjects in the gait experiment had a decrease in their subhallux pressure (Fig. 6).

Relationships were investigated between the change in dorsiflexion or subhallux pressure and body weight, left and right foot, gender, shoe size, resting calcaneal stance position, and change in resting calcaneal stance position. None of the correlations were found to be statistically significant. The same was true comparing nonweightbearing range of motion with improvement in the maximum degree of dorsiflexion or subhallux pressure.

To examine the correlation between nonweightbearing and weightbearing range of motion and change in first metatarsophalangeal joint motion, we measured the difference between nonweightbearing and weightbearing range of motion, and then ranked the results. We then ranked the same results according to the outcome range of joint motion using the Spearman rank correlation. There was no statistically significant association of the variant between weightbearing and nonweightbearing range of motion and the resulting increase in dorsiflexion.
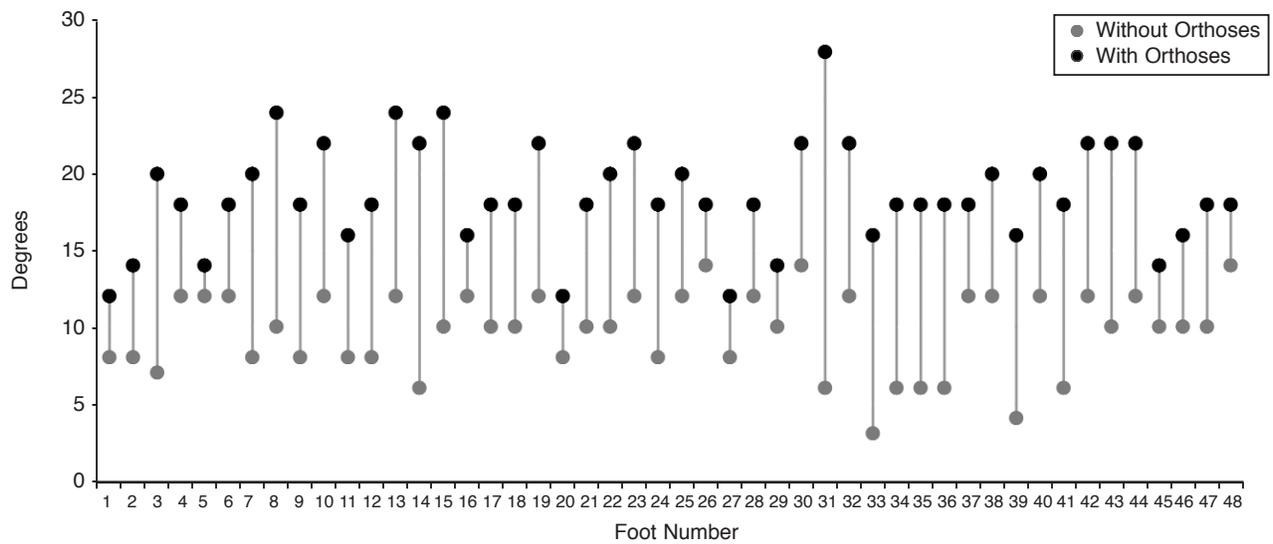
Figure 5. Increase in degrees of maximum dorsiflexion in stance.

Similarly, the effect of resting calcaneal stance position on dorsiflexion was measured using the Spearman rank correlation. The ρ value of –0.45 was well below the necessary cutoff value of 0.324. There was no statistically significant correlation between the change in resting calcaneal stance position and the change in dorsiflexion.

Discussion

The null hypothesis stated that the orthosis made from a negative cast with the first ray plantarflexed and a 4-mm medial skive does not affect first metatarsophalangeal joint dorsiflexion in either stance or gait. The results of this study do not support the null
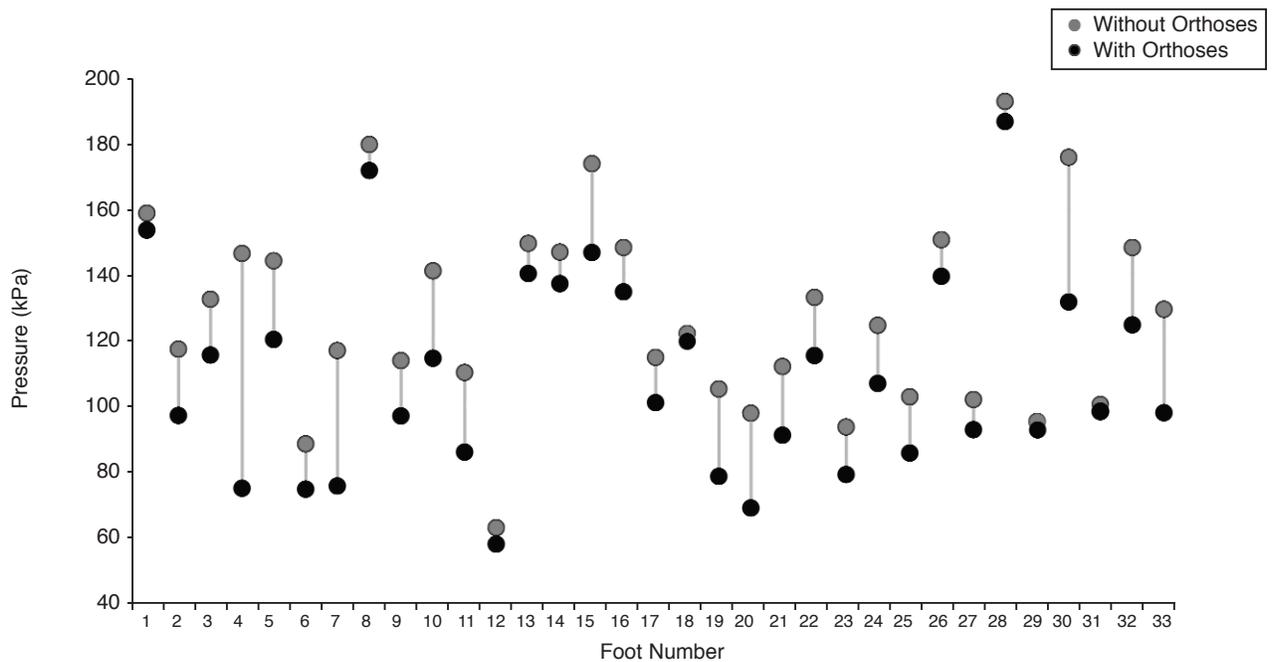
Figure 6. Decrease in maximum subhallux pressure in gait.

hypothesis and instead suggest that an orthosis made from a cast with the first ray plantarflexed and a 4-mm medial skive can increase the maximum degree of dorsiflexion in patients with limited dorsiflexion in stance and gait.

If the mechanical limitation of functional hallux limitus in the presence of forced dorsiflexion created by heel-off contributes to the development of deformities, including hallux valgus and hallux rigidus, then an orthosis that increases the range of dorsiflexion might contribute to the reduction of symptoms of these deformities. Furthermore, if the range of dorsiflexion can be improved by repositioning the first ray by using an orthosis before surgery, this may represent a positive prognostic sign for patients undergoing surgery for hallux valgus or hallux rigidus.

The data suggest that change in position of the foot using an orthosis made from a cast with the first ray plantarflexed and a 4-mm medial skive increased the freedom of motion of the first metatarsophalangeal joint in gait. We speculate that this may eventually contribute to the treatment of subhallux pathology related to excessive pressure under the hallux during the heel-off portion of gait.

This study did not compare the orthotic effect of orthoses that were not made from a cast with the first ray plantarflexed. We contend that the specific negative casting method used produces an orthosis that increases forward pitch, or plantarflexion of the first ray, and, therefore, increases the freedom of motion of the first metatarsophalangeal joint. There may be a comparable result if the negative cast is made without plantarflexing the first ray.

We suspect that if the dorsiflexion of the metatarsophalangeal joint can be increased, then the effectiveness of treatment of hallux abducto valgus and hallux rigidus with orthotic therapy will improve. Further investigation is warranted to determine whether symptoms are reduced or surgical prognosis is improved using this pathology-specific orthosis.

Conclusion

A functional Root-type orthosis was constructed from a neutral-suspension plaster cast by positioning the first ray at the plantarflexed end of its range of motion and using a 4-mm medial skive. The device, manufactured according to a specific prescription, was given to subjects who met the criteria for functional hallux limitus, and a resulting quantitative increase in range of motion was measured in all of the subjects. The device was then tested in a subgroup of subjects to determine whether there was a decrease in subhallux pressure from the beginning of heel-off to toe-off in gait. The data revealed a quantitative decrease in subhallux pressure during gait in all of the subjects. We propose that a specific functional orthosis manufactured from a cast with the first ray plantarflexed alters the pitch of the first ray by raising the proximal position and increases the range of dorsiflexion and freedom of motion of the first metatarsophalangeal joint. We recognize that the 4-mm medial skive modification may also have contributed to the findings of the study. The exact causes of the effects are unknown.

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