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Functional Motion of the Medial Column Joints of the Foot During Propulsion

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Motion in the ankle, subtalar, midtarsal, and first metatarsophalangeal joints has been well documented. However, motion in the first metatarsocuneiform, the first cuneonavicular, and the first interphalangeal joint has not been addressed. Motion in these joints has not been documented because many believe that little motion occurs at these joints, and because of the difficulty in assessing motion at these joints. Using two-dimensional motion analysis, the authors present sagittal plane ranges of motion occurring in the first metatarsophalangeal joint, the first metatarsocuneiform joint, the medial cuneonavicular joint, and the first interphalangeal joint during the propulsive period of gait. This pilot study indicates that sagittal plane motion between the navicular and calcaneus and between the first metatarsal and first cuneiform are very mild and inconsistent. However, plantarflexion motion between the first cuneiform and the navicular is significant and comprises most of the plantarflexion motion of the first ray during propulsion. Motion in the first interphalangeal joint is slight during the first 80% of the propulsive period but shows slight-to-moderate dorsiflexion during the last 20% of the propulsive period of gait.

The propulsive period of gait has been described in terms of the motion of the foot relative to the ground, and also in terms of quantitative motion occurring in the metatarsophalangeal joint and a qualitative motion in an ill-defined joint known as the "first ray." The purpose of this study is to determine the motions of each individual segment of the medial column of the foot during the propulsive period of gait.

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Background

First Metatarsophalangeal Joint Motion

The metatarsophalangeal joint functions as a ginglymoarthrodial-type joint. It is generally accepted that to walk normally, 65° to 75° of sagittal plane dorsiflexion is required.[1] This minimal requirement is because of the positioning of the tibia during its final stage of propulsion. At this stage, the tibia is tilted approximately 45° forward from vertical, and the foot is plantarflexed at the ankle, at approximately 20°. The first metatarsal must be capable of plantarflexing and gliding in a plantar proximal fashion relative to the base of the proximal phalanx. This allows the transverse axis of the first metatarsophalangeal joint to shift more dorsally and proximally,

thus allowing the dorsal aspect of the first metatarsal to articulate with the base of the proximal phalanx. It is this shift in the transverse axis and the decreasing of the linear distance between the first metatarsal head and the calcaneus that allows a large range of motion in the first metatarsophalangeal joint during propulsion.[2]

Considerable variations continue to exist when defining the normal range of motion of the first metatarsophalangeal joint. In 1937, Hiss[3] reported the average range of motion at the first metatarsophalangeal joint to be 90°, with the amount of plantarflexion and dorsiflexion equally divided at 45°. However, he did not indicate the method by which he determined these values. The first significant determination of the range of motion was reported by Joseph[4] in 1954. He made measurements in 50 male subjects from radiographs taken when the longitudinal axes of the metatarsal and phalanx were in alignment. He found the average range of motion in open kinetic chain to be 90.8°. This value continues to be reported as the normal total range of motion in the first metatarsophalangeal joint.[5]

Kelikian[6] determined the average range of hallux dorsiflexion to be 70°, but he did not indicate whether this was closed kinetic chain motion or open kinetic chain motion. Mann[7] and Mann and Hagy[8] stated that 30° to 40° of motion is required to clear the toe from the ground, and 70° to 90° of motion should be considered normal. However, they did not indicate how they arrived at these data, except that it was during walking.

Sgarlato[9] stated that the normal range of motion at the first metatarsophalangeal joint is between 50° and 80°. Bojsen-Moller and Lamoreux[10] found a mean of 58° of motion of the first metatarsophalangeal joint at toe-off, using still video capture. By the angle created when bisecting the lateral proximal phalanx and the lateral first metatarsal during active and passive motion, Gerbert[11] determined the range of motion of the first metatarsophalangeal joint. He concluded that 60° to 65° of motion is needed to prevent jamming and subsequent damage to the articular surface. However, this method was nonweightbearing, and therefore may not reflect an accurate assessment of the range of motion in closed kinetic chain.

Buell et al[2] also examined the range of motion in the first metatarsophalangeal joint. They used landmark identification to determine the range of motion, and concluded that their values were close to those obtained by Joseph. In comparing the two methods, they determined the average range of motion to be between 89° and 90°, depending on the method used. They then used assisted dorsiflexion, which they believed represented closed kinetic chain motion, and reported the average clinical value of motion in the first metatarsophalangeal joint to be 105°.

Hetherington et al[12], in a study conducted on 60 feet, determined the range of dorsiflexion of the first metatarsophalangeal joint to be 25° to 41° in the right foot and 30° to 40° in the left foot. In this study, they assumed the first metatarsophalangeal joint was maximally dorsiflexed when there was palpable dorsiflexion of the first metatarsal. In a second study on 60 feet, Hetherington et al[13] found the average value of dorsiflexion at the first metatarsophalangeal joint to be 50° to 56° ± 4.45°. Findings in both studies by Hetherington et al were determined in closed kinetic chain motion.

In 1990, Shereff[14] stated that the hallux is able to dorsiflex nearly 90°; however, for normal weightbearing ambulation, only 70° is needed. Hopson et al[15] found the range of motion in the first metatarsophalangeal joint to range between 89° and 116.7° in static nonweightbearing; between 90° and 107.3° in static partial weightbearing; between 92° and 142.3° in static weightbearing step length; and between 51° and 81.7° in dynamic walking.

First Ray Motion

In 1953, Hicks[16] identified an axis of motion for the first ray that proceeded from proximal medial to distal lateral. He indicated that the first ray dorsiflexes on the rearfoot with a lowering of the calcaneal inclination angle. He noted a change at 18°, with the normal calcaneal inclination angle being between 15° and 25°.

Root et al[1] stated that the plantarflexion of the first ray is necessary for normal dorsiflexion of the first metatarsophalangeal joint. They noted that as the first ray dorsiflexes, the range of motion available at the first metatarsophalangeal joint diminishes, while any plantarflexion of the first ray will cause an increase in the range of motion in the first metatarsophalangeal joint.

D'Amico and Schuster[17] described a noticeable dorsiflexion and eversion in the first ray when there was accompanying rearfoot pronation; however, they did not quantify the amount of motion observed. A study in 1982 by Kelso et al[18] determined the average total sagittal plane range of motion for the first metatarsal was 12.38 mm ± 3.4 mm. They also measured significant inversion rotation of the first ray relative to the second ray when it was dorsiflexed and eversion rotation when it was plantarflexed.

Ebisui[19] found, when pronatory forces were

applied to the forefoot, the first ray extended with little demonstrable inversion. However, as the pronatory force increased, extension decreased, and inversion increased. He noted that the first ray was hypermobile at this point. He also found primary motion in the first metatarsocuneiform joint to be flexion and extension with only a small amount of rotary motion. At the end range of motion in the first metatarsocuneiform joint, the joint appeared to have a locking mechanism. When the first metatarsocuneiform joint was locked, and increasing extensory force was applied, rotation occurred at the medial cuneonavicular joint, with the medial cuneiform rotating medially away from the intermediate cuneiform.

Ketai et al[20] noted that if the first ray showed excessive dorsiflexion and inversion, the amount of dorsal excursion available at the proximal phalanx is limited, which allows for dorsal jamming to occur at the first metatarsophalangeal joint. Using cadaveric specimens, Ouzounian and Shereff[21] determined the range of motion of the medial cuneonavicular joint, in plantarflexion and dorsiflexion, to be between 0.7° and 8.7° with a mean of 2.3°. They determined the plantarflexion-dorsiflexion range of motion at the first metatarsocuneiform articulation to be between 1.9° and 5.3°, with a mean of 3.5°. In supination-pronation, the range of motion in the medial cuneonavicular joint joint is between 3.5° and 9.9°, with a mean of 7.3°. In supination-pronation, the motion observed in the first metatarsocuneiform was found to range from 0.0° to 2.6°, with a mean of 1.5°.

Wanivenhaus and Pretterklieber[22] determined several ranges of motion at the first tarsometatarsal joint. They are as follows: dorsal displacement of 2.6 mm, abduction of 4.4°, adduction of 5.0°, eversion of 6.2° after dorsal displacement, inversion of 4.1° after dorsal displacement, abduction after dorsal displacement of 5.8°, and adduction of 5.0° following dorsal displacement. Using a modified Coleman block test, Fritz and Prieskorn[23] found the sagittal plane range of motion at the first metatarsocuneiform joint to be 4.37°. The range of motion in the first ray required to allow the necessary 65° of hallux dorsiflexion has not yet been studied.[1]

Interphalangeal Joint Motion

The range of motion in the interphalangeal joints during gait has never been assessed in the literature. Root et al[1] stated that some plantarflexion motion is necessary at the interphalangeal joints, but the minimal range is unknown.

Materials and Methods

Ten female volunteers, between the ages of 22 and 38 years, were selected for the study. All subjects were free of clinical symptoms of the lower extremity. The weight of each volunteer varied from 120 to 200 pounds. Each subject was told to walk barefoot across a walkway 16 feet long at her normal gait speed. A super VHS video camera was placed perpendicular to the subject at the center of the walkway to capture the medial aspect of the subject's foot. The camera recorded the stance phase of the gait cycle at a rate of 60 fields per sec and a shutter speed of 1/500 sec. Each subject walked at least three paces before entering the camera field, and each walked in front of the camera at least three times.

A total of 12 flat, high-visibility reflective markers, ¼-inch in diameter, were placed directly on the skin of the medial aspect of the right foot. An attempt was made to place them on skin areas that had the smallest amount of skin motion over the bone. These locations were as follows: point 1) calcaneal tubercle, point 2) sustentaculum tal, point 3) dorsomedial surface of the navicular, point 4) plantar medial surface of the navicular, point 5) proximal portion of the medial cuneiform, point 6) distal portion of the medial cuneiform, point 7) proximal shaft of the first metatarsal, point 8) distal shaft of the first metatarsal, point 9) proximal shaft of the first proximal phalanx, point 10) head of the first proximal phalanx, point 11) base of the first distal phalanx, and point 12) tuft of the first distal phalanx (Fig. 1).

The recorded images were digitized using the PEAK 5.0 motion analysis software®. Heel-off was determined to be the frame just prior to first visualization of a space between the heel and the ground. Toe-off was determined to be the frame prior to seeing a space between the tuft and the ground. When points could not be visualized because of the swing foot passing in front of the stance foot, these points were interpolated using the same software.

The following angular relationships were defined and calculated by the software: 1) the angle between the plantar surface of the foot (defined by points 1 and 8) and the horizontal; 2) the angle between the calcaneus (defined by points 1 and 2) and the horizontal; 3) the angle between the navicular (defined by points 3 and 4) and the horizontal; 4) the angle between the medial cuneiform (defined by points 5 and 6) and the horizontal; 5) the angle between the first metatarsal (defined by points 7 and 8) and the

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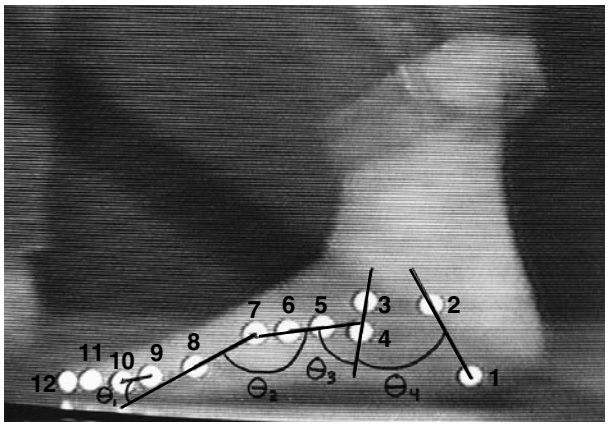

Figure 1. Medial side of the foot during late propulsion. The segments are marked as follows: the calcaneus by points 1 and 2, the navicular by points 3 and 4, the cuneiform by points 5 and 6, the first metatarsal by points 7 and 8, the proximal phalanx by points 9 and 10, and the distal phalanx by points 11 and 12.

horizontal; 6) the angle between the first proximal phalanx (defined by points 9 and 10) and the horizontal; 7) the angle between the first distal phalanx (defined by points 11 and 12) and the horizontal; 8) the angle between the navicular and the calcaneus; 9) the angle between the medial cuneiform and the navicular; 10) the angle between the first metatarsal and the medial cuneiform; 11) the angle between the first proximal phalanx and the first metatarsal; and 12) the angle between the first distal phalanx and the first proximal phalanx.

After calculating the angles, the propulsive period of gait was normalized for each subject using a free-end cubic spline to express a value for each percentage of the propulsive period of gait. In addition, all of the angles were expressed relative to the "zero value," which was the initial value for each angle at the beginning of propulsion. By normalizing all of the values in this way, the graphs of the subjects could be compared with each other.

Results

The field of view width was between 16 and 18 inches. Because of the small viewing field, most of the trials were discarded because one or more points were out of the camera view for part of the stance phase of gait. Only 22 trials for the ten subjects were used, with one to three trials for each subject. Because of the small number of usable trials for each subject and also because the subjects walked at a slightly different cadence for each trial, each trial was treated as a separate event.

For all subjects, there was a forward rotation (ie, counterclockwise) of the calcaneus, the navicular, first cuneiform, and first metatarsal through the entire propulsive period of gait. At no time did any segment show a plantargrade rotation. Table 1 presents the maximum angular rotation of the heel, navicular, cuneiform, and metatarsal relative to the ground from heel lift to toe-off. The greatest degree of segment rotations during propulsion was in subject B, while the least degree of segment rotations during propulsion was in subject C.

Figure 2 shows the average foot-to-floor angle increasing in an exponential fashion through propulsion. The average foot rotated 54° from the moment of heel-off until toe-off. However, the first 45% of propulsion was spent in the first 10° of rotation and an additional 20% of propulsion was spent in rotating the next 10°. It is noted that half of the angular rotation of the foot and the ground does not occur until the subject was approximately 75% through the propulsive period.

There was no significant difference at the $p < 0.01$ level in the average maximum rotation of the calcaneus and the average maximum rotation of the navicular. Likewise, there was no significant difference at the $p < 0.01$ level in the average maximum rotation of the first metatarsal and the average maximum rotation of the first cuneiform. However, there was significantly more rotation of both the metatarsal and the cuneiform than of the navicular and the calcaneus. Table 2 shows that at the 99% confidence level, the first cuneiform rotated forward 11° to 26° more than the calcaneus. The first cuneiform rotated 12° to 28° further forward than the navicular. Thus, the authors conclude that there is significantly more forward rotation distal to the cuneonavicular joint than proximal to the cuneonavicular joint. The only way that these rotations could happen is for a significant plantarflexion motion of the first cuneiform relative to the navicular and almost no net plantarflexion motion of the navicular relative to the rearfoot or of the metatarsal relative to the cuneiform.

Figure 3 shows the average rotation forward of each of these four segments relative to the ground through the propulsive period of gait. A visual inspection of the graph shows that all four segments rotate forward to approximately the same degree during the first 45% of the propulsive period. At this point, the first metatarsal starts rotating forward a little faster than the other three segments, indicating that there is a mild degree of plantarflexion occurring at the first metatarsocuneiform joint. At approximately 64% of the propulsive period, the first cuneiform starts rotating forward faster than the navicular and calcaneus,

Table 1. Maximum Angle Change for Each Segment with the Ground During the Propulsive Period of Gait

Subject	Total Foot-to-ground Angle	Heel-to-ground Angle	Navicular-to-ground Angle	Cuneiform-to-ground Angle	Metatarsal-to-ground Angle
A1	-42.5	-33.1	-32.2	-46.9	-53.2
A2	-50.6	-38.9	-35.3	-55.5	-60.0
B1	-63.8	-48.1	-48.4	-81.6	-66.1
B2	-69.2	-52.4	-51.9	-89.3	-73.3
C1	-45.8	-40.2	-36.2	-47.1	-51.7
C2	-41.8	-34.5	-34.5	-49.6	-48.4
C3	-41.4	-34.6	-29.7	-45.8	-46.2
D1	-57.3	-47.7	-50.2	-68.7	-68.1
D2	-62.8	-54.0	-59.3	-69.9	-68.2
D3	-57.6	-46.6	-46.1	-64.9	-66.4
E1	-59.3	-49.8	-46.3	-64.2	-66.4
F1	-45.9	-36.3	-39.6	-54.0	-52.2
F2	-57.7	-46.3	-43.7	-65.8	-65.1
G1	-47.9	-41.4	-43.2	-56.2	-50.6
G2	-46.3	-45.4	-42.9	-50.9	-46.6
G3	-50.4	-42.6	-43.0	-58.3	-52.3
H1	-50.8	-40.4	-40.0	-60.3	-58.2
H2	-48.9	-39.0	-34.6	-56.7	-56.6
H3	-55.1	-44.2	-41.8	-63.7	-60.0
I1	-64.8	-48.1	-45.9	-74.9	-73.5
J1	-60.3	-48.8	-42.2	-76.3	-61.3
J2	-60.9	-50.4	-46.9	-73.6	-61.3
Average	-53.7	-43.8	-42.5	-62.5	-59.3
Standard deviation	8.2	6.1	7.0	11.8	8.4

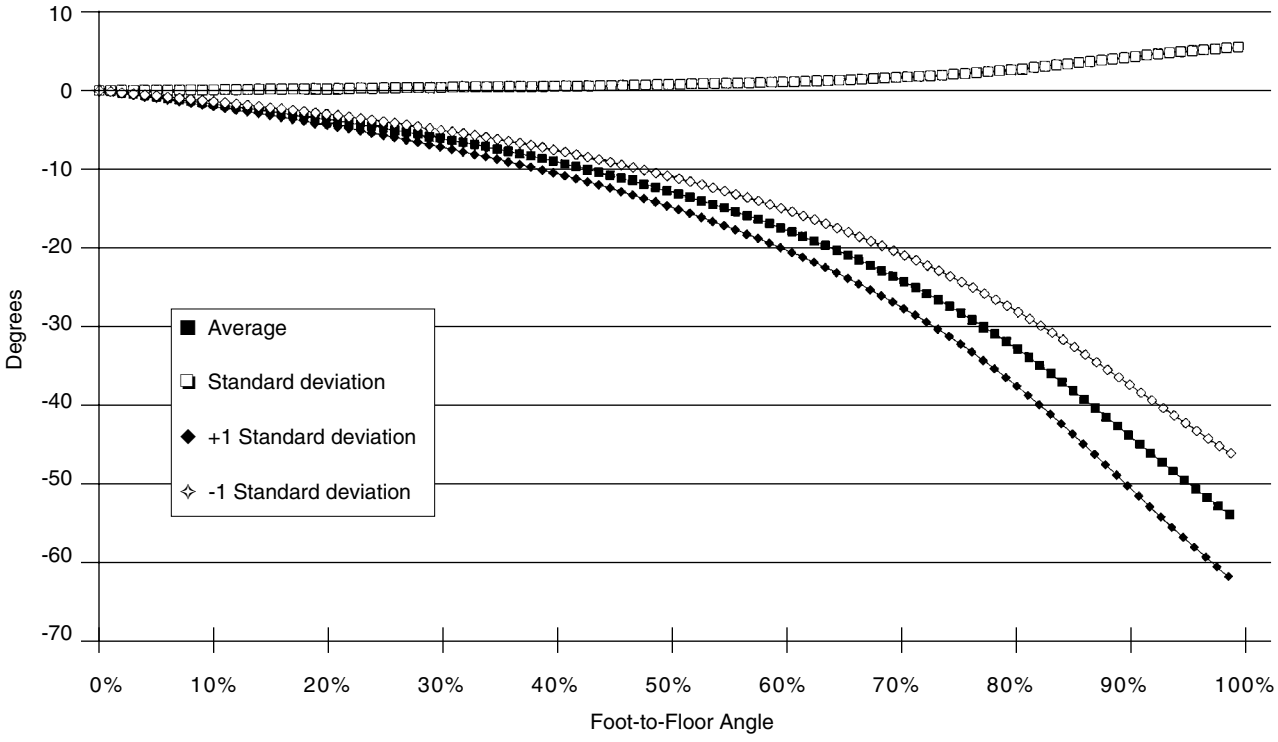

Figure 2. The angle of the plantar aspect of the average foot in this study rotated 54° between heel-off and toe-off. The first 20° of motion encompasses the first two thirds of the propulsive period.

Table 2. Confidence Table at the 99% Level Comparing the Amount That Each Segment Rotated Relative to Each Segment

Segment	1% Confidence Difference	Upper Difference	Lower Difference
Foot *versus* heel to ground	5.8553571	-4.1	-15.8
Total foot *versus* navicular to ground	6.1906144	-5.0	-17.4
Total foot *versus* cuneiform to ground	8.277171	17.1	0.5
Total foot *versus* metatarsal to ground	6.7370415	12.4	-1.1
Heel *versus* navicular to ground	5.3240548	4.0	-6.6
Heel *versus* cuneiform to ground	7.6507132	26.3	11.0
Heel *versus* metatarsal to ground	5.950595	21.5	9.6
Navicular *versus* cuneiform to ground	7.910241	27.9	12.1
Navicular *versus* metatarsal to ground	6.2807708	23.2	10.6
Cuneiform *versus* metatarsal to ground	8.3448148	5.2	-11.5

indicating that plantarflexion motion is occurring at the first cuneonavicular joint. At 80% of the propulsive period, the cuneiform and metatarsal are equally rotated forward. The cuneiform continues to rotate a little faster than the metatarsal through the remainder of propulsion, indicating that a mild dorsiflexion motion is occurring at the metatarsocuneiform joint.

A graph of the average cuneonavicular angle is shown in Figure 4. The navicular and cuneiform show almost no angular change for the first 64% of the propulsive period, and then afterward, there is a nearly straight linear plantarflexion at the cuneonavicular joint until the end of propulsion where the joint is approximately 20° plantarflexed from its starting position. When the average cuneonavicular angle is plotted against the average metatarsopha-

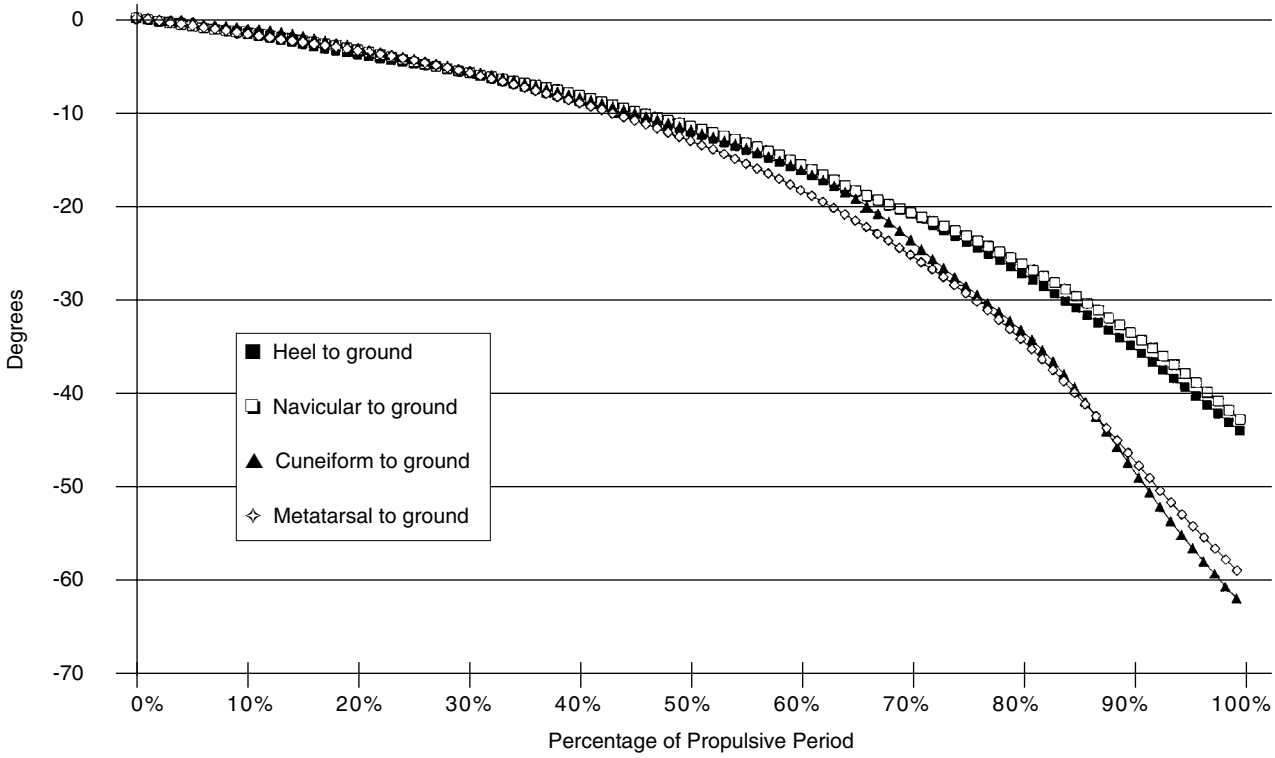

Figure 3. For the first 10° of propulsion, all segments proximal to the metatarsophalangeal joint move together. From 10° to 20° of propulsion, the metatarsal rotates more slightly than the other three segments, indicating plantarflexion at the metatarsocuneiform joint. After 20° of propulsion, the cuneiform also starts rotating much faster than the navicular and calcaneus indicating significant plantarflexion motion occurring at the cuneonavicular joint.

langeal joint angle in Figure 5, it is noted that this linear plantarflexion begins just about the time when the metatarsophalangeal joint has reached the first 20° of its dorsiflexion movement. It is also noted that the forward rotation of the cuneiform from this point on has a greater downward slope than the first metatarsal until it reaches the same rotation as the first metatarsal at 75% of the propulsive period. This means that there is actually a mild degree of dorsiflexion occurring at the first metatarsocuneiform joint from 64% to the end of the propulsive period.

Figure 6 shows the average metatarsophalangeal joint angle through the propulsive period of gait. The maximum average angle of metatarsophalangeal joint dorsiflexion was only 45°, which occurred at 95% of the propulsive period of gait. However, the maximum dorsiflexion velocity occurred at 80% of the period. From here on, the dorsiflexion velocity decelerated. During this time, the metatarsal-to-ground angular velocity continued to accelerate. Figure 7 shows that the reason this occurred was because at about the time the metatarsophalangeal joint started decelerating, the proximal phalanx started a forward rotation. For the last 20% of the propulsive period, the metatarsophalangeal joint increased its dorsiflexion angle only 12°, while the proximal phalanx increased its angle to the floor by approximately 15° and the distal phalanx increased its angle to the ground by 8° (Fig. 8). This means that the average interphalangeal joint dorsiflexed approximately 7° from its starting position.

The dorsiflexion motion in the interphalangeal joint during the last 20% of propulsion was compared with how much metatarsophalangeal joint motion occurred, to see if the interphalangeal joint extension was a result of failure of the metatarsophalangeal joint to dorsiflex. Figure 9 shows the plot of the maximum interphalangeal joint dorsiflexion *versus* the maximum metatarsophalangeal joint motion for each trial. A linear regression line with Pearson's correlation coefficient of -0.62 shows that less metatarsophalangeal joint motion tends to create greater degrees of interphalangeal joint dorsiflexion during the propulsive period of gait.

Discussion

It is important to recognize that this study is only a pilot study and thus, the information presented shows only a trend that deserves further investigation. Since the only criteria used for selection of subjects were age, sex, and lack of subjective com-

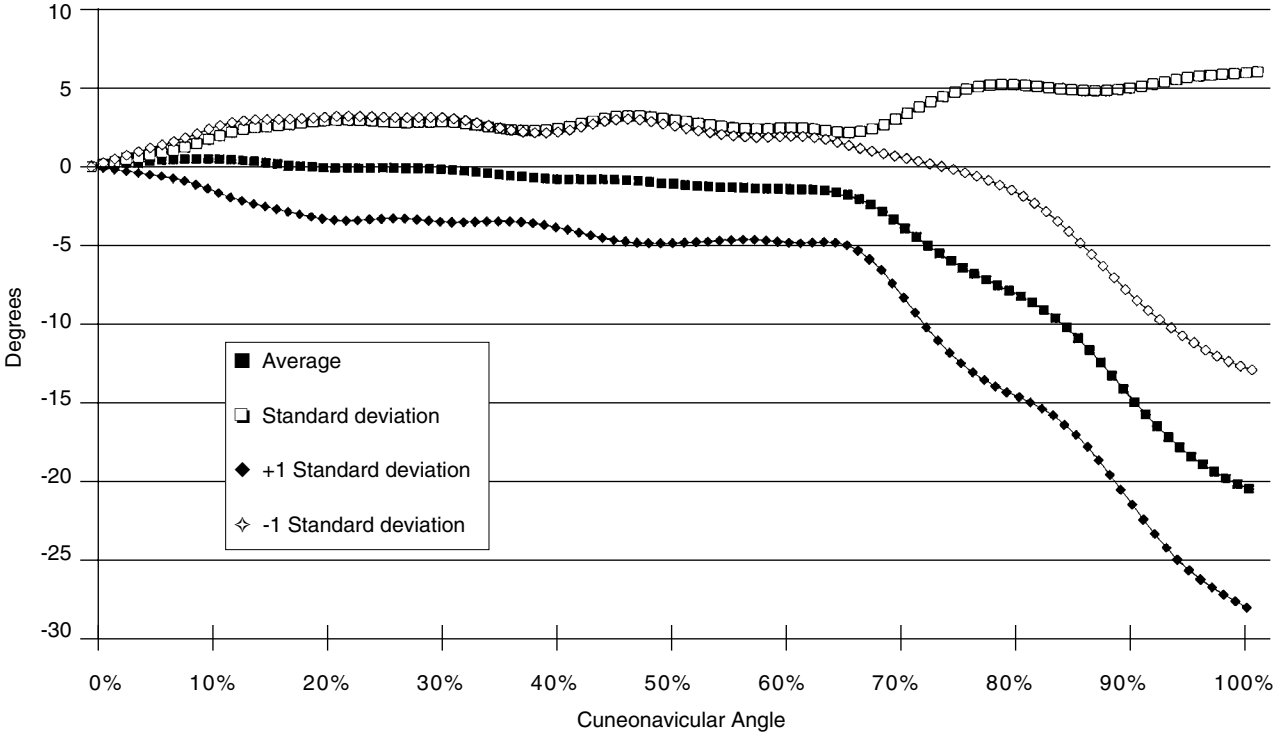

Figure 4. The cuneonavicular angle stays constant during the first two thirds of the propulsive period, followed by an average of 20° of plantarflexion during the last third of the propulsive period.

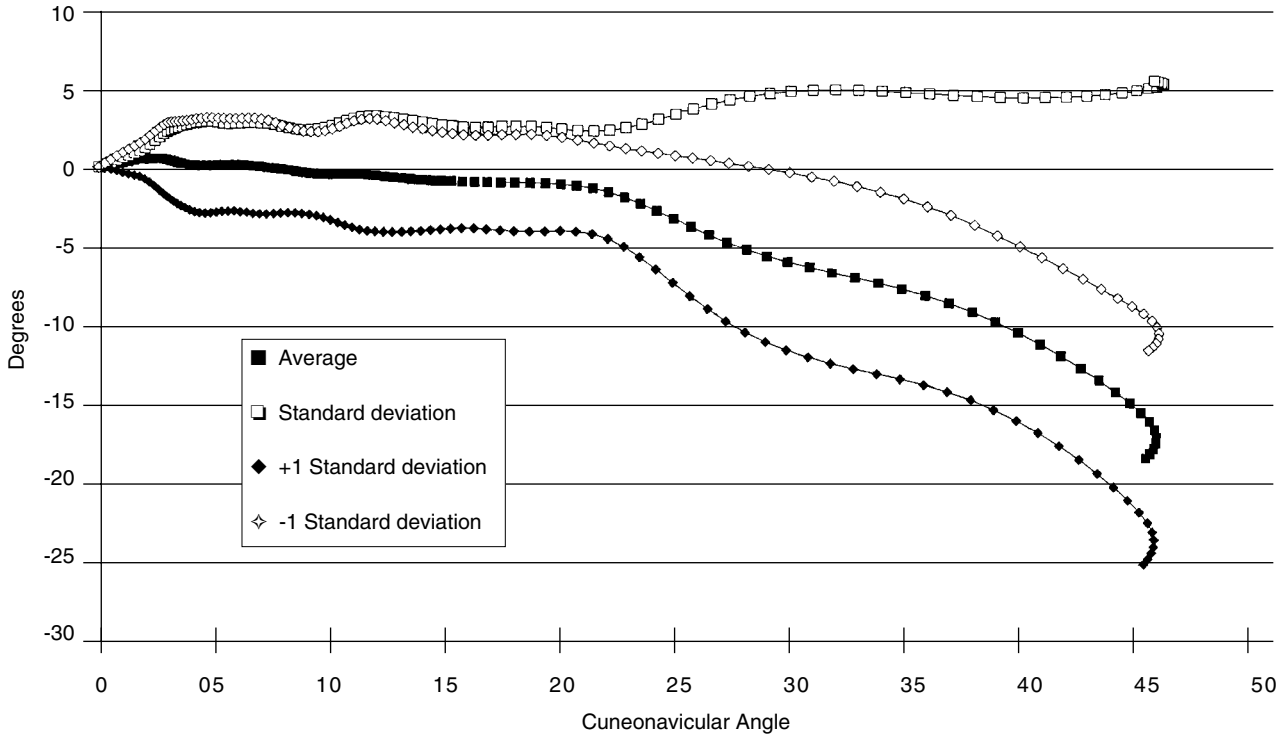

Figure 5. The cuneonavicular angle changes little during the first 20° of metatarsophalangeal joint dorsiflexion. After 20° of first metatarsophalangeal joint dorsiflexion, the cuneonavicular joint plantarflexes in a linear fashion at a rate of approximately 0.7° for every 1° of metatarsophalangeal joint motion.

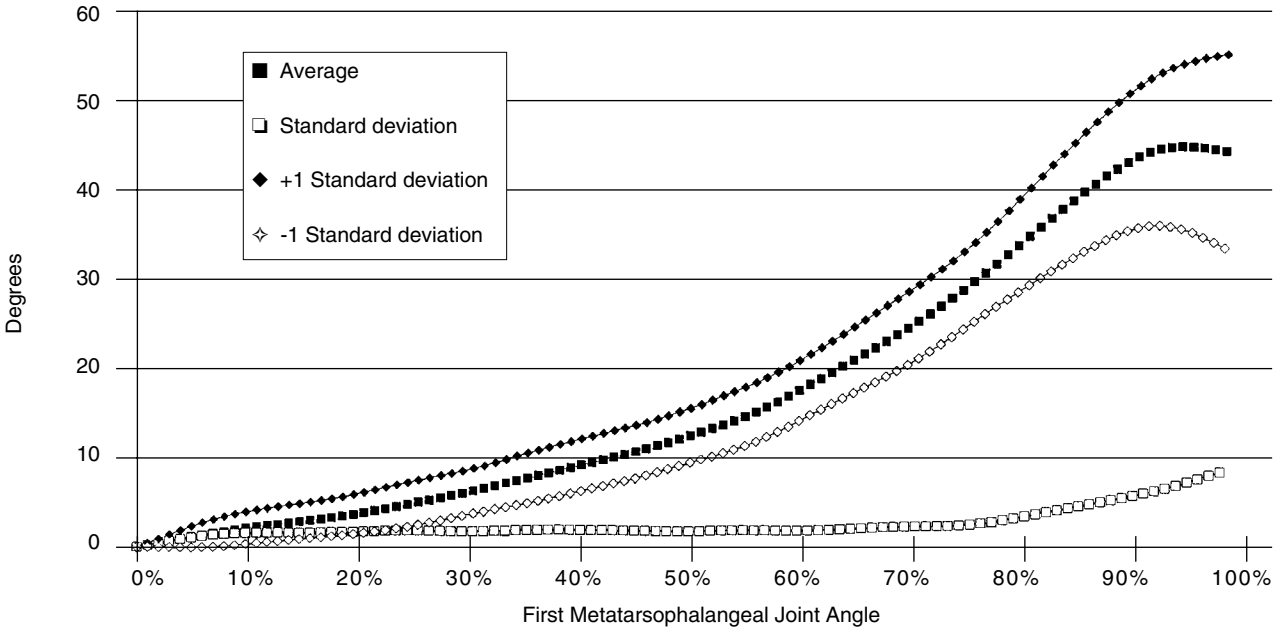

Figure 6. The first metatarsophalangeal dorsiflexed in an exponential fashion for the first 90° of the propulsive period. The average for this study's group was 45° ± 8°. This is slightly less than what is considered to be normal dorsiflexion. During the last 10% of the propulsive period, the foot continued to rotate forward around the first interphalangeal joint.

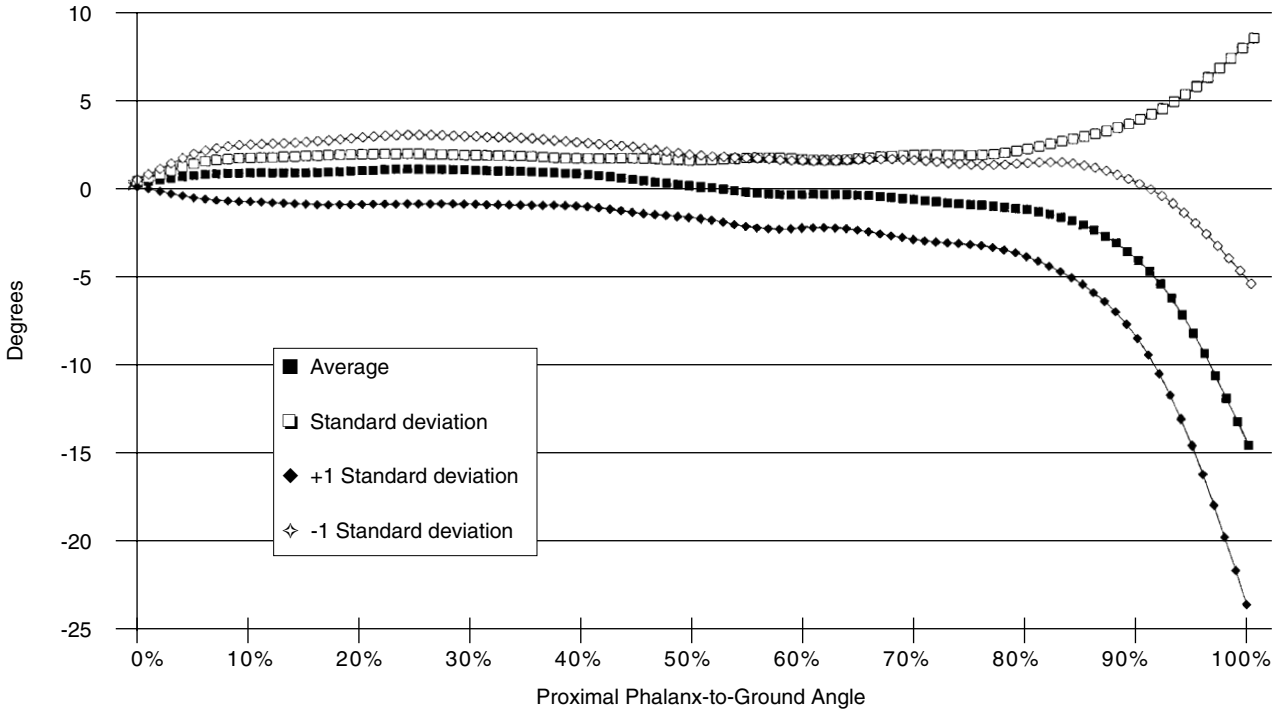

Figure 7. The proximal phalanx stayed fixed relative to the ground during the first 80% of the propulsive period. It then rotated forward in an exponential fashion approximately 15° before the toe left the ground.

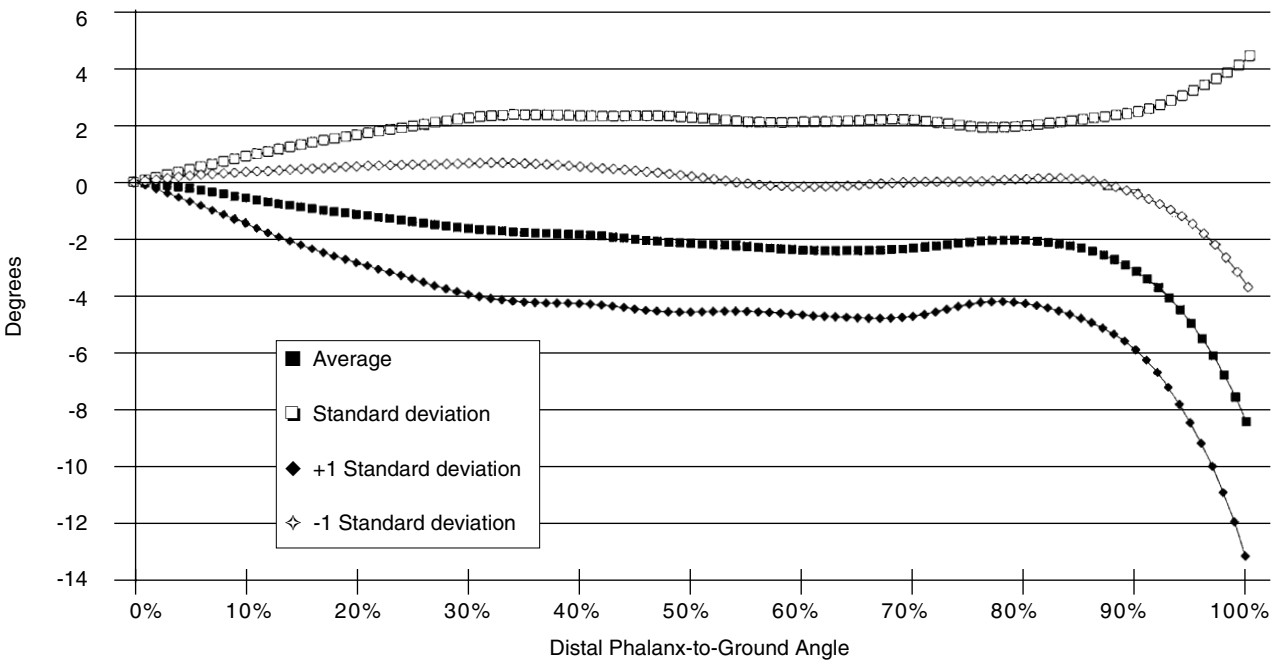

Figure 8. The distal phalanx showed very little rotation during the first 90% of the propulsive period. It also rotated forward during the last 10% of propulsion, but only half as much as the proximal phalanx. The difference between the distal and proximal phalanx rotations was caused by dorsiflexion motion in the interphalangeal joint.

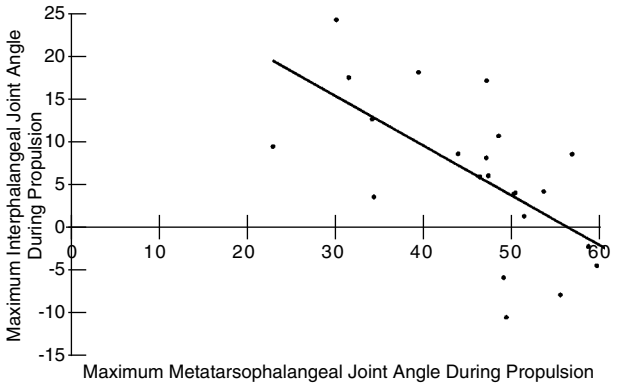

Figure 9. A plot of the amount of interphalangeal joint motion during propulsion shows an inverse correlation between the amount of metatarsophalangeal joint motion and the amount of interphalangeal joint motion. The less metatarsophalangeal joint motion the patient experiences, the greater the interphalangeal joint dorsiflexion that can be expected.

plaints, the data presented here as the average data should not necessarily be construed as data for the "normal population." Certainly, some of these subjects had limited metatarsophalangeal joint motion as defined by previously noted standards. The lack of symptoms by these subjects to date should not be construed to mean that a slow, pathologic process is still not occurring that will result in the development of symptoms.

The range of motion in the interphalangeal joint, in this study, is a preliminary finding and is only significant in that no author has previously established a range of motion for this joint. It has been previously documented that increased interphalangeal joint motion can occur following arthrodesis and extreme hallux limitus.[24] This study shows that failure of the metatarsophalangeal joint to dorsiflex adequately can produce interphalangeal joint hyperextension. However, the interphalangeal joint dorsiflexed to some extent in almost all of the subjects as the metatarsophalangeal joint dorsiflexed late in the propulsive phase, and there was not a perfect linear regression between the amount of metatarsophalangeal joint motion and the interphalangeal joint motion. This would then indicate that the interphalangeal joint dorsiflexion may contribute a role in the heel lifting off the ground during propulsion, even in subjects with adequate metatarsophalangeal joint motion.

The metatarsophalangeal joint range of motion determined in this study is similar to that previously described by other authors.[3, 4] It was noted that in all subjects, metatarsophalangeal joint dorsiflexion does not occur in a linear fashion but has an exponential increase in velocity from heel lift to approximately 75% of the propulsive period. From here until the end of propulsion, there is a decrease in the dorsiflexion velocity while the proximal phalanx starts lifting from the ground. This lifting of the proximal phalanx would correspond with the literature of the flexor hallucis longus muscle becoming quiescent at this point in the gait cycle.

The plantarflexion motion of the first metatarsal relative to the calcaneus has long been recognized in order to allow the hallux to dorsiflex. Hicks[16] attributed this to the windlass mechanism of the plantar aponeurosis. The degree of plantarflexion necessary for the first metatarsal has never been reported. Figure 10 shows the maximum angular change of the first metatarsal relative to the calcaneus for the subjects in this study. A linear regression line through the points, with a Pearson's correlation coefficient of r = -0.80, confirms this correlation. This regression line would intersect the x-axis at 18°, which approaches the commonly accepted value of 20° of metatarsophalangeal motion before the first ray starts plantarflexing. This line would then predict that in order for the hallux to dorsiflex 60°, 22° of first ray plantarflexion would have to occur.

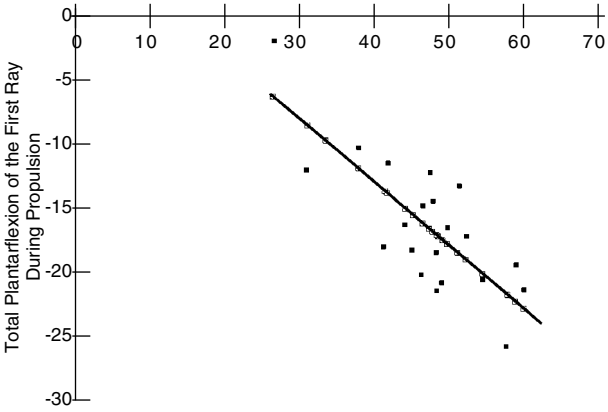

Figure 10. A plot of the amount of total plantarflexion of the first ray and the amount of metatarsophalangeal joint dorsiflexion that the patient experiences shows a high correlation between the two. Extrapolating the linear regression line predicts that 20° of metatarsophalangeal joint motion may be experienced without any net plantarflexion of the first ray. After that, the net plantarflexion of the first metatarsal relative to the rearfoot would be approximately 1° of plantarflexion for every 3° of first metarsophalangeal joint dorseflexion.

Hicks[16] described an axis of the first ray passing from posterior medial and slightly superior to anterior lateral and slightly inferior. He did not describe how much motion was occurring in which of the joints that make up the first ray. This study shows that almost all of the plantarflexion motion of the first ray occurs at the cuneonavicular joint. In fact in most of the authors' subjects, the net plantarflexion of the first ray was a little less than the plantarflexion of the cuneonavicular joint. A Pearson's product moment correlation coefficient between first cuneonavicular joint plantarflexion and first metatarsophalangeal joint dorsiflexion shows only an r = -0.53, a much lower value than the correlation coefficient between the net first ray plantarflexion and the metatarsophalangeal joint. This indicates that there was some type of equalization function between the first cuneonavicular joint and the joint distal and proximal in which if the first cuneonavicular joint plantarflexed more, the other two joints dorsiflexed a little more to keep the net plantarflexion motion closer to a smoothly progressive line. No pattern of how this interaction between these three joints occurs could be detected in this small study, a study that did not try to distinguish various foot types.

The authors believe that the major plantarflexion motion occurring at the cuneonavicular joint is consistent with a number of clinical phenomena. For example, the peroneus longus has been shown to assist in plantarflexion force of the first ray during propulsion. Yet examination of the anatomy shows that the peroneus longus inserts into both the first metatarsal and the first cuneiform. This means that a contraction of the peroneus longus would apply a plantarflexion motion at the cuneonavicular joint rather than at the first metatarsocuneiform joint. Likewise, the anterior tibial also inserts into the first metatarsal and the first cuneiform. Therefore, contraction of the anterior tibial would be more likely to produce motion in the cuneonavicular joint than in the metatarsocuneiform joint.

Surgical fusions of the medial column joints for various deformities or dysfunctions have been advocated through the years. The Lapidus operation for bunion deformity fuses the first metatarsocuneiform joint. This study would indicate that the surgeon need not be overly concerned that fusion of this joint could produce deformity. However, fusions of the cuneonavicular joint, such as those that have been advocated for the treatment of flatfoot deformity, may carry a significant risk of producing hallux limitus after surgery. The fusion of the midtarsal joint does not appear to directly produce a significant adverse effect on the ability of the hallux to dorsiflex, although blocking talonavicular motion may still block digital propulsion by indirect mechanisms.

While the role of first ray plantarflexion has been considered in discussing the range of motion of the first metatarsophalangeal joint, little has been said about the role of the plantarflexion motion of the first ray in contributing to ankle joint and knee joint motion during propulsion. As was mentioned earlier, the forward rotation of the calcaneus relative to the ground was an average of 15° less than the rotation of the metatarsal to the ground. The reason that the calcaneus can rotate less than the first metatarsal during propulsion is that the first ray plantarflexes relative to the rearfoot. Now what would happen if the calcaneus had to rotate as far forward as the first metatarsal during propulsion?

Figure 11 shows the diagram of segments of the foot as they occurred in the frame before toe lift as they actually occurred in trial 2 of subject F. A comparison is made with what the foot position would have been had none of the intrinsic foot joints moved when the first metatarsal dorsiflexed. It is noted that the lines representing the leg and the ankle would have had to rotate 17° further forward if the first ray had not plantarflexed. In other words then, first ray plantarflexion has necessitated less ankle joint plantarflexion during propulsion. Less ankle joint plantarflexion then will necessitate less knee joint flexion during propulsion and less hip joint flexion during propulsion. If the knee and hip joints do not have to flex as much, then the patient will be able to move his or her body mass higher on the propulsive side.

As noted earlier, this is a pilot study that shows a definite trend in the movements of the individual joints of the medial column of the foot during propulsion. It is recognized that this is a sagittal plane view and in no way represents the total motion of these joints, which would also include frontal and transverse plane motions. It is also noted that the study relies on markers attached directly to the skin and there has been no attempt to try to find how much skin motion occurred over the bones during the propulsive period of gait. Although there may have been skin motion over the bony landmarks, it is doubtful that the skin motion between the cuneiform and navicular could have been so much greater than the skin motion between the metatarsal and cuneiform, nor between the navicular and calcaneus. Further studies must include the skin motion factor, but the skin motion cannot be held responsible for the great differences between the joints. Thus, the authors believe that interpretation of the skin marker movements about the underlying joint movements is correct.

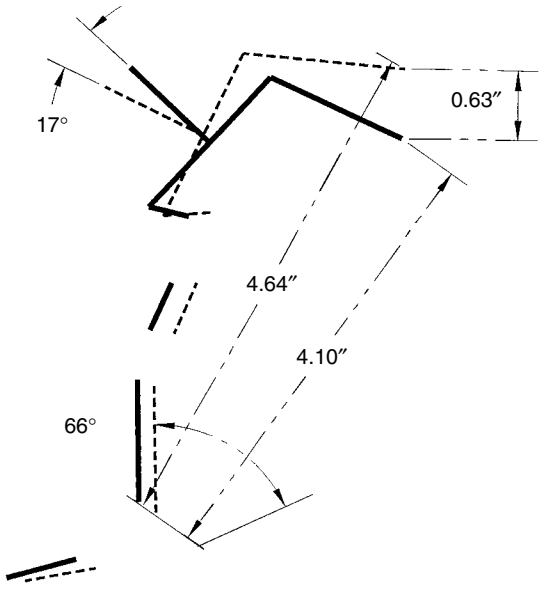

Figure 11. A diagram of the segments of the foot for trial F2. The dark solid lines are the segments at maximum metatarsophalangeal joint motion of 66° from the beginning of propulsion. The dotted lines show what the foot segment relationships would be if the metatarsophalangeal joint had rotated the same 66° but none of the joints proximal had moved. A solid line perpendicular to the line connecting the calcaneus and navicular segments represents the leg. Comparing these two drawings with each other shows that first ray plantarflexion accounts for a 10% decrease in length between the first metatarsal head and the calcaneus. It also shows that first ray plantarflexion results in the heel not needing to rise off the floor as much, and also that the tibia does not have to move as far forward as it would if the first ray did not plantarflex.

Conclusion

The authors have shown that the interphalangeal joint has a determinable range of motion in female subjects during propulsion. Almost all had a slight plantarflexion motion during the first two thirds of propulsion followed by a mild-to-moderate dorsiflexion movement. In addition, the range of motion of all of the joints of the first ray can be measured in degrees and points to the cuneonavicular joint as providing the majority of plantarflexion motion of the first ray, allowing dorsiflexion of the first metatarsophalangeal joint.

Further research needs to be conducted with a larger sample pool, taking into consideration skin motion and various foot types to confirm these findings. Three-dimensional motion analysis will aid in determining frontal and transverse plane motions, and also if the cuneonavicular and metatarsocuneiform joints have their own separate axes of motion.

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ERRATA

In "California Liaison Committee for Podiatric Medical Education and Training," by Drs. Medio, Stess, and Naylor, August 1996, the following errors occurred:

p. 366, right column: "5) conducting the first meetings of representatives of the podiatric medical profession with the University of California's Council of Medical School Deans and its Council of University Hospital Administrators;"

p. 368, left column: "With the support of both the medical and podiatric licensing boards . . . "

p. 369, left column: "Initial funding support for the committee came from the licensing board, California Podiatric Medical Association,"