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ORIGINAL RESEARCH

Biomechanics of the First Ray. Part II: Metatarsus Primus Varus as a Cause of Hypermobility. A Three-Dimensional Kinematic Analysis in a Cadaver Model

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Variation in functional stability of the first metatarsocuneiform joint was analyzed between transverse plane deviated (adducted) and corrected first metatarsal positions in a closed kinetic chain model. Six fresh frozen cadaver specimens with intact ankles and feet were fitted with a custom fabricated titanium metatarsal jig, which allowed for manipulation of the first metatarsal in the transverse plane. Specimens were mounted into a custom-made acrylic load frame and axially loaded to 400 N. Radiowave three-dimensional tracking transducers were attached to the following osseous segments: first metatarsal head and base, medial cuneiform, and second metatarsal. A dorsally directed load was applied to the first metatarsal segment and resultant movements were measured. Repeated testing was performed on a transverse deviated and corrected first metatarsal positions with the hallux plantargrade and maximally dorsiflexed to engage the windlass mechanism. With the windlass mechanism engaged and first metatarsal corrected, a 26% increase in first ray plantarflexion occurred from a deviated to a corrected first metatarsal position ($p \leq .05$). This suggests that the windlass mechanism is more efficient when the first metatarsal, sesamoid apparatus, and hallux position are properly aligned with the orientation of the plantar aponeurosis. Clinically, this may explain the correlation of first ray hypermobility with the progression of bunion severity. Our study validates the earlier work of Hicks and adds additional insight into the functional stability in the medial column of the foot. (The Journal of Foot & Ankle Surgery 39(2):68-77, 2000)

Key words: first ray hypermobility, foot biomechanics, windlass mechanism

The normal closed kinetic chain mechanics of the first ray have long been taken as an understood phenomenon. However, after careful analysis of past research and rhetorical debate, it becomes evident that pathomechanical conditions of the first ray (i.e., hallux abductovalgus (HAV) and first ray hypermobility) may not be completely understood. Morton, an anatomist, was the first to develop the concept of first metatarsal insufficiency and hypermobility, and correlated intrinsic foot pathology to clinical dysfunction (1-4). He described insufficiency of the first metatarsal as being caused by a short or hypermobile segment. Since that time, authors have contributed to the intellectual concept of first ray hypermobility (5-8), but to date, the etiological factors remain an enigma. Many authors have made very astute clinical observations with eloquent descriptions of first ray motion and its importance in gait, although many of these observations were based on empiric data (9-12). Recent authors have described hypermobility of the first ray in a qualitative

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fashion (5, 13–15) and others have looked at hypermobility in patients who had clinical evidence of an insufficient first ray (16).

The normal weightbearing function of the first ray results from a delicate balance between the ground reactive forces and supporting structures that stabilize the medial column. The structures most responsible for first ray stability are plantar ligaments, extrinsic muscles inserting onto the first ray, and the plantar aponeurosis. Any variable that compromises this intrinsic balance can lead to abnormal function and progressive deformity of the first ray. Deformities such as HAV are likely associated with biomechanical dysfunction. However, quantitative assessment of many of these biomechanical relationships is lacking. The importance in defining the relative structural contributions and influencing factors which govern first ray motion are obvious. Eventually, it will lead to more accurate clinical assessment and a more logical and objective preoperative procedure selection, as well as better long-term prognoses and improved functional outcomes.

Functional Considerations of the Medial Column

Anatomically, the plantar aponeurosis (PA) is divided into three bands of specialized connective tissue, which are attached to the plantar calcaneal tuberosity. The central band has the most significant functional influence on the foot. Distally, the central band inserts into the skin and plantar fat pads of the forefoot and its deeper components blend with the plantar plates of the lesser digits and the sesamoid bones of the first metatarsophalangeal joint (17–22).

As the hallux goes through a dorsal excursion in motion, tensile load is generated in the PA through a linkage classically described by Hicks as a windlass effect (23). The relationship between the windlass mechanism and its arch-raising effect received little attention in the early literature (24), until later investigations highlighted its importance (23). It was Hicks in 1953 who began to critically evaluate the importance of the PA as well as the internal architecture of the foot (23, 25, 26). He was the first to demonstrate the windlass phenomenon in a cadaver specimen and concluded it must therefore be relatively independent of muscular control. The PA has a characteristic ligamentous type response to mechanical loads. Under low loads it behaves elastically, whereas under greater loads it resists deformation (27). Ker et al. (28) found that the PA acted somewhat like a spring and was able to store enough strain energy to be a significant stabilizing force in the stability of the medial arch. Their study also found that the long and short plantar ligaments as well as the spring ligament have significant stabilizing roles in the static structure of the foot. Furthermore, they concluded that tension created in the PA is sufficient enough to be used for both energy storage in locomotion and stabilization of the medial column of the foot.

The importance of the PA in static stabilization of the medial column has been clearly demonstrated in investigations where various static supporting structures were individually sectioned and the foot loaded (29, 30). Thordarson et al. (31) found a 25% reduction in medial arch stiffness with complete sectioning of the PA. Huang et al. (32) documented that the greatest amount of medial arch collapse occurred after release of the PA when compared to isolated other structures, such as the long and short plantar ligaments and spring ligament. A biomechanical model developed by Kim et al. (33) showed that the PA carries as much as 14% of the pedal load-bearing capacity, which also demonstrates degeneration of foot load tolerance with arch lowering.

Retrograde forces created by the activation of the extrinsic muscles have also been implicated in increased transverse plane motion of the first ray (34). The level at which this transverse plane motion occurs in the medial column and the implications on the function of the peroneus longus (PL) is still a matter for further delineation.

First Ray Hypermobility

A strict definition of first ray hypermobility remains elusive with its characterization being based predominantly on qualitative parameters (2, 5, 6, 11, 13–15, 24, 35, 36). First ray hypermobility has been described as an excessive dorsal excursion with a soft end point. Fritz et al. (37) attempted to evaluate several factors associated with hypermobility and failed to show a statistical correlation between first ray motion, age, sex, intermetatarsal angle 1–2, skin stretch, hyperextension of the elbow and knee, or shape of the distal cuneiform. The only variable they found as a consistent predictor of first ray hypermobility was hyperextensibility of the thumb (38). It was Klaue et al. (16) who proposed that hypermobility was a significant factor in formation of HAV deformity. They studied first ray mobility using patients with clinical hallux valgus deformity. With a custom-modified ankle-foot orthosis, they were able to document motion in the sagittal plane with a center of rotation just distal to the naviculocuneiform joint. Carl et al. (15) showed a correlation between symptomatic hallux valgus and a generalized hypermobility when compared to control groups.

The first ray axis is triplanar and has been described by previous authors (11, 12) and has varied regarding whether the motion measured was observed in open (16, 37–40) or closed kinetic chain (Table 1) (20, 23, 32, 41–45). Wanivenhaus et al. (46), in a cadaveric study, added additional insight into the complexity of the first ray function. They documented that motion of the first

TABLE 1 Motion of the first ray as previously documented

Study	Results
Hicks (25)[a]	Axis from middorsum of foot over the base of the third metatarsal to the navicular tuberosity. Flexion-pronation, extension-supination. 22° ± 8°.
Klaue et al. (16)[b]	5.3 ± 1.4 mm of sagittal displacement of metatarsal head in control feet compared to 9.3 ± 1.9 mm in feet with HAV. 1.5 ± 0.7 mm of sagittal displacement of metatarsal base in control feet compared to 2.6 ± 1.4 mm in feet with HAV. Sagittal axis of rotation just distal to naviculocuneiform joint.
Firtz and Prieskorn (37)[a]	6.93° of sagittal rotation of first ray in patients with hyperextensibility of the thumb compared to 3.95° of sagittal rotation in patients without a hyperflexible thumb. Normal rotation was found to be 4.37°. No correlation between shape of metatarsocuneiform joint and sagittal motion of first ray was found.
Wanivenhaus and Pretterklieber (46)[a]	Only 10% of specimens showed adduction (avg. 5.0°) or abduction (avg. 4.4°). Eversion of the first ray (avg. 6.2°) occurs only after translation of the first metatarsocuneiform joint (avg. 2.6°).
Kelso et al. (39)[b]	12.38 ± 3.4 mm of total sagittal plane range of motion of the first ray.
Mizel (20)[a]	5 mm of dorsal displacement of the metatarsal base relative to the cuneiform with sectioning of plantar ligaments.
Johnson and Christensen (41)[a]	Peroneus longus activity created 8.06° ± 3.07° and 7.44° ± 2.64° of eversion of the first metatarsal and first cuneiform respectively. PL action also created 3.8° ± 0.54° and 2.97° ± 0.57° of plantarflexion of the first metatarsal and first cuneiform respectively.

[a]Closed kinetic chain
[b]Open kinetic chain

ray occurs at different levels within the medial column. In addition, they demonstrated there was a considerable amount of motion that occurred at the intercuneiform 1–2 and naviculocuneiform joints with lateral compression of the metatarsal heads. Other important factors must also be considered in first ray hypermobility. Mizel (20) showed, in a cadaveric study, that by cutting the plantar ligaments to the first metatarsocuneiform joint, he could create as much as 5 mm of dorsal displacement of the metatarsal relative to the cuneiform. This suggests that the plantar soft-tissue structures are very important in preventing dorsal translation at the metatarsocuneiform joint level. Romash et al. (36) described and classified an articulation between the bases of metatarsals one and two, but the significance of this facet in motion in the first ray is still unclear. In part I of this series of investigations, the influence of PL on first ray function was evaluated (41). It was found that PL created a significant amount of motion in the direction of eversion, essentially locking the medial cuneiform into the medial column.

The purpose of part II in this series of investigations is to define the role of the plantar aponeurosis in stabilizing the first ray via the windlass mechanism in a cadaver model with pre-existing metatarsus primus varus (MPV) and hallux abductovalgus deformity. It was hypothesized in this study that MPV, as well as associated HAV, and sesamoid malposition play a major role in destabilization and hypermobility of the first metatarsal segment. The literature supports the hypothesis that the PA should play a large static role in stabilization of the medial column during midstance (30–33, 42, 43, 45, 47–48). Further, we wanted to determine how much stability could be restored to the first ray with deformity correction through a simulated proximal metatarsal osteotomy.

Material and Methods

Specimen Acquisition and Preparation

Seven fresh frozen cadaver lower limb specimens with pre-existing MPV deformity and HAV were obtained from the Department of Biological Services at the University of Washington. All specimens had intact feet and ankles and were deep frozen to −20°C. Before testing all specimens underwent radiographic screening using a specially designed loading frame to simulate a weightbearing situation. Anteroposterior and lateral radiographs were taken of all feet and a tarsal index was recorded for each specimen as described by Benink (49). This enabled the classification of foot type for each specimen tested. Radiographic evaluation of all specimens was done to measure absolute intermetatarsal angle and sesamoid position (Table 2). All specimens were visually inspected for joint space narrowing, osseous pathology, and malalignment of the rearfoot. Tibial sesamoid position was recorded as the amount of lateral displacement of the tibial sesamoid compared to the bisection of the first metatarsal shaft. The shape of the metatarsocuneiform joint and lateral aspect of the first metatarsal base were recorded as previously described (36, 37). All first metatarsals were

TABLE 2 Tarsal index as well as anatomic characteristics of all specimens

Specimen	Tarsal Index	Sesamoid Position	Lateral Facet (29)	First MCPJ Facet (45)	Absolute IM Angle
1	8	4	None	III (> 20°)	13
2	10	5	Transitional	II (10–20°)	14
3	7	4	Transitional	III (> 20°)	13
4	6	5	Facet	II (10–20°)	14
5	4	4	Transitional	II (10–20°)	12
6	7	5	None	II (10–20°)	12

visually surveyed prior to testing to ensure that none had any appreciable amount of coronal rotation of the first metatarsal that could interfere with sesamoid realignment. If any valgus rotation of the metatarsal was present, specimens were excluded from the study. One specimen was eliminated at this phase due to previous surgery to remove a tibial sesamoid, which left six specimens for testing.

Before testing, all specimens were thawed to room temperature and all soft tissue was removed down to the level of the joint capsule and periosteum, taking special care to preserve the integrity of the capsuloligamentous structures. A specially designed titanium alloy metatarsal jig was then placed into the first metatarsal segment (Fig. 1, A and B). The metatarsal jig was a two-component articulated implement that allowed for manipulation of the intermetatarsal angle 1–2. To facilitate placement of the metatarsal jig, a louvered polyvinylchloride osteotomy guide was specially designed and pretested to precisely remove a 15-mm block of diaphyseal bone from the first metatarsals of all specimens. The osteotomies were made perpendicular with the long axis of the metatarsal. The metatarsal jig was secured into the metatarsal bone using small Kirschner wires. This configuration was pretested and was shown to be a rigid construct which

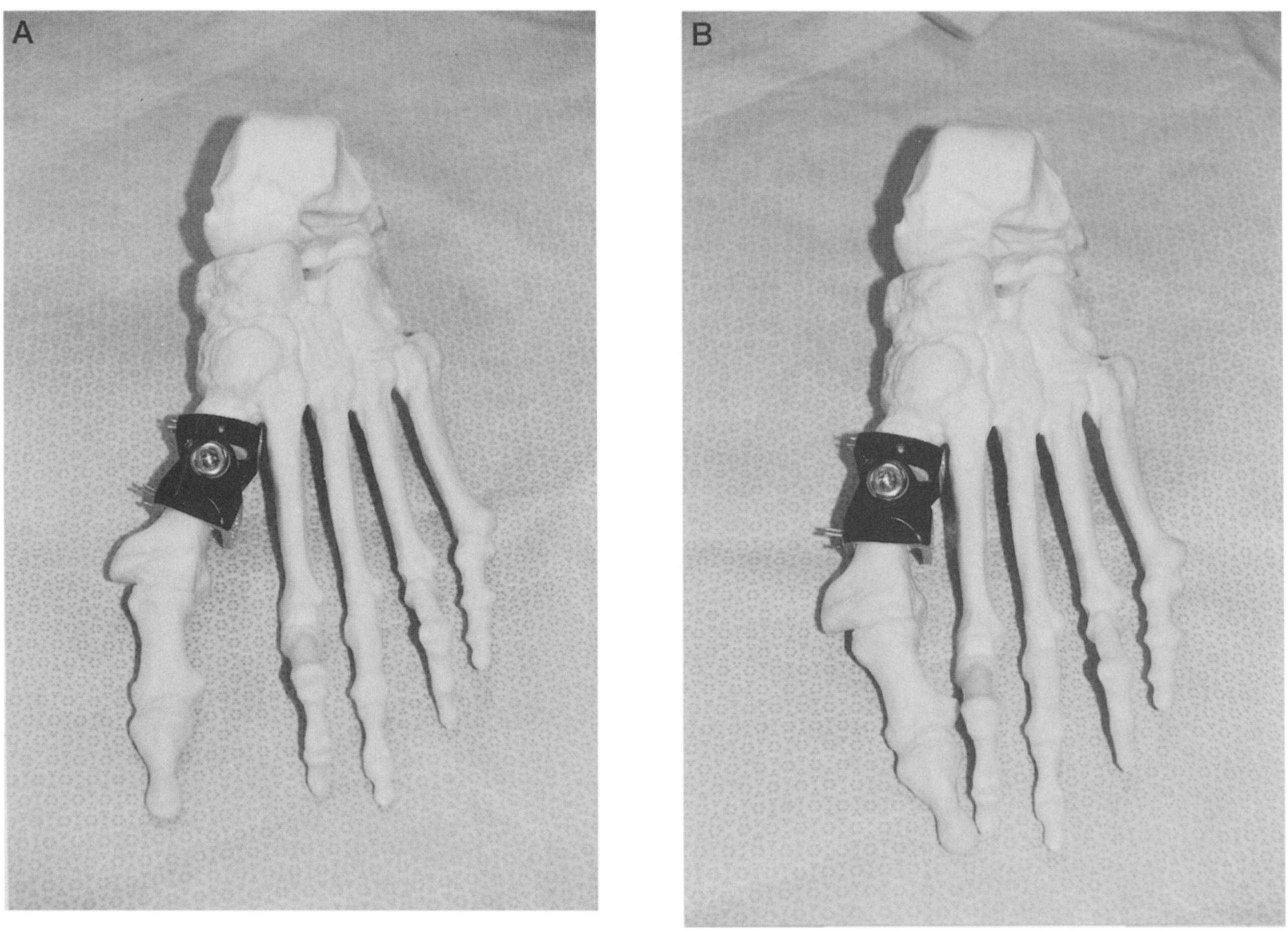

FIGURE 1 Metatarsal jig inserted into a saw bone model with a large intermetatarsal angle (*A*) and with a corrected intermetatarsal angle (B).

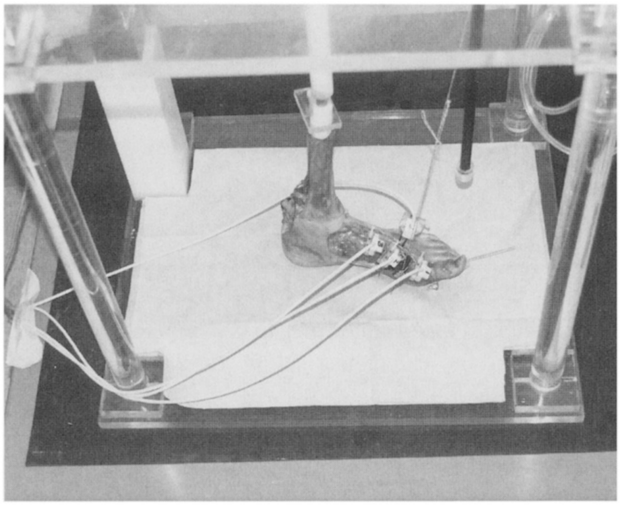

FIGURE 2 Cadaver specimen loaded into load frame with metatarsal jig in place. First metatarsophalangeal joint pinned in maximum dorsiflexion with radiowave tracking sensors in place.

would withstand repetitive load frame testing without displacement, as well as allow for controlled manipulation of the intermetatarsal angle 1–2.

The Load Frame

All specimens were loaded into a vertically oriented custom acrylic load frame.[4] A pneumatic load cylinder at the top of the frame allowed for axial loading of each specimen through a polycarbonate rod fitted into the tibia and fibula. This configuration allowed for near physiologic loading. The specimens were placed on a nonskid surface to prevent slippage during testing and all feet were allowed to settle in resting stance position for testing (Fig. 2).

Three-Dimensional Tracking System and Sensor Attachment

Four receiving transducers from a radio signal tracking system[5] were attached to four osseous segments: metatarsal head and base, cuneiform one, and second metatarsal. The radio signals were collected at a rate of 30 Hz and the positions of each sensor were determined. Computer algorithms then converted the radio signals to data points. The system has a resolution of 0.0005 cm/cm of range and .025° of rotation and accuracy within .08 cm RMS and .15° RMS (50). The Fastrack® system enables four osseous segments to be tracked in three dimensions simultaneously. The system tracks motion in a global coordinate system using 6 degrees of freedom (linear displacements along the *X*, *Y*, and *Z* coordinates and rotational displacements about each axis). The Cartesian coordinates were set in reference to a source box affixed to the load frame. Use of metal implements in the testing area was avoided as they could interfere with the radiowave tracking system. Pretesting confirmed that the titanium alloy jig had no deleterious influence on the radiowave tracking system.

Each sensor was attached by two carbon fiber rods that were secured to each of the four osseous segments to be analyzed. Sensor placement on each side of the metatarsal jig ensured that any aberrant motion occurring in the metatarsal construct would be picked up in data analysis. Also, sensor placement into the second metatarsal ensured that no frontal plane motion of the lesser rays occurred.

Testing Protocol

After being attached to the load frame with sensor application to the osseous segments, all specimens were taken through a predetermined testing protocol. A pneumatic air cylinder attached to a synthetic cord was anchored to the metatarsal jig. The cylinder functioned to create a dorsally directed force of 100 N on the first metatarsal through the metatarsal jig. For each testing situation, baseline data were taken before and after manipulation of the jig. The protocol was as follows: large intermetatarsal angle 1–2 with hallux plantargrade and large intermetatarsal angle 1–2 with maximum dorsiflexion of the hallux (windlass engaged). At this point the intermetatarsal angle was reduced to less than 5° via the metatarsal jig and the sesamoids were repositioned under the metatarsal head in their respective grooves. The protocol was then repeated: rectus ray with hallux plantargrade and rectus ray with maximum dorsiflexion of the hallux (windlass engaged). Vertical loading was only applied for the brief time in which data were being collected to minimize the amount of soft-tissue creep in the fascia during the testing. Further, taking a new zero point after manipulation of the intermetatarsal angle 1–2 eliminated the cumulative effect soft-tissue deformation would have on the last sets of data collected. Separate data were taken for each position of the osseous segments and saved for statistical analysis.

Statistical Analysis

Post acquisition processing of the data for each specimen was performed on a personal computer using two custom software programs as well as a statistics software program.[6] All kinematic data were analyzed using a Wilcoxin ranked pair test to compare changes in motion of the osseous segments for significant values at $p \leq .05$. The data were analyzed with the Wilcoxin ranked pair

[4] Designed by Bioconcepts, Inc., Seattle, WA and fabricated by Advanced Biomedical, Inc., Oakland, CA.

[5] Fastrack®, Polhemus Inc., Colchester, VT.

[6] Statview 4.0, Abacus Systems, Berkley, CA.

test because the baseline for each testing situation had to be re-established after manipulation of the intermetatarsal angle. The testing protocol did not allow for continuous data sampling.

Results

Motion of the first ray in a closed kinetic chain model was compared with both deformity (MPV, HAV) and with a corrected first ray. The amount of closed kinetic chain sagittal motion was recorded for each segment of the first ray. The plantarflexion of the first ray with the hallux plantargrade and with the windlass engaged was against a vertical force centered at the first ray and thus was an expression of rigidity in the first metatarsal segment in resisting dorsal displacement. Results showed an increased ability to engage the windlass mechanism and plantarflex the first ray with restoration of first ray alignment.

Metatarsal Sagittal Motion

The difference in sagittal motion (plantarflexion around the *y* axis) of the metatarsal head in specimens with deformity (MPV, HAV), with the hallux plantargrade compared to hallux dorsiflexion (windlass engaged) was 1.21° ± 2.67°. This difference in plantarflexion was not found to be significant ($p = .177$). After correction of the first ray, sagittal motion (plantarflexion around the *y* axis) with the hallux plantargrade compared to hallux dorsiflexion (windlass engaged) increased to 4.08° ± 1.91°. This increase in plantarflexion was significant ($p = .0277$) (Fig. 3).

The difference in sagittal motion (plantarflexion around the *y* axis) of the metatarsal base in specimens with deformity (MPV, HAV) with the hallux plantargrade compared to hallux dorsiflexion (windlass engaged) was 1.38° ± 3.86°. This difference in plantarflexion was not found to be significant ($p = .177$). After correction of the first ray, sagittal motion (plantarflexion around the *y* axis) with the hallux plantargrade compared to hallux dorsiflexion (windlass engaged) increased to 5.37° ± 1.36°. This increase in plantarflexion was significant ($p = .0277$) (Fig. 4).

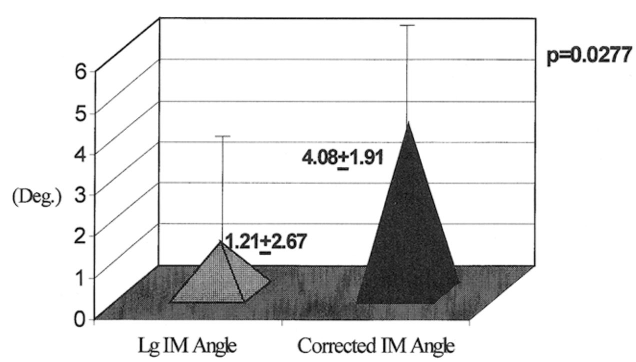

FIGURE 3 Difference in sagittal motion (plantarflexion around the *y* axis) of the metatarsal head in specimens with deformity (MPV, HAV) and with deformity corrected. Hallux plantargrade compared to hallux dorsiflexion (windlass engaged).

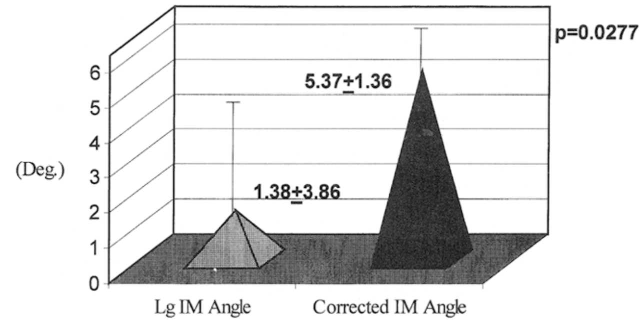

FIGURE 4 Difference in sagittal motion (plantarflexion around the *y* axis) of the metatarsal base in specimens with deformity (MPV, HAV) and with deformity corrected. Hallux plantargrade compared to hallux dorsiflexion (windlass engaged).

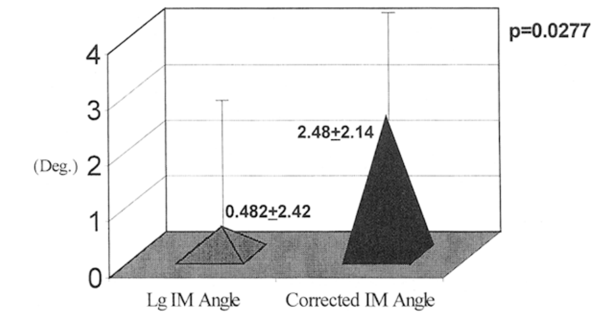

FIGURE 5 Difference in sagittal motion (plantarflexion around the *y* axis) of the cuneiform in specimens with deformity (MPV, HAV) and with deformity corrected. Hallux plantargrade compared to hallux dorsiflexion (windlass engaged).

Cuneiform

The difference in sagittal motion (plantarflexion around the *y* axis) of the cuneiform in specimens with deformity (MPV, HAV) with the hallux plantargrade compared to hallux dorsiflexion (windlass engaged) was 0.482° ± 2.42°. This difference in plantarflexion was not found to be significant ($p = .177$). After correction of the first ray, sagittal motion (plantarflexion around the *y* axis) with the hallux plantargrade compared to hallux dorsiflexion (windlass engaged) increased to 2.48° ± 2.14°. This increase in plantarflexion was significant ($p = .0277$).

Metatarsal Jig Sagittal Motion

There was a difference of 1.29° ± 0.67° in sagittal plane motion between the metatarsal head and base. This motion was attributed to a lack of stiffness in the metatarsal jig construct. The intrinsic motion in the metatarsal jig was recorded using a sensor on each side of the jig. This ensured that motion intrinsic to the metatarsal jig construct could be evaluated if it occurred. The differential motion between the metatarsal head and base was not statistically significant ($p = .177$).

Discussion

Hypermobility of the first ray can be conceived of as a continuum of increasing pathomechanical motion which has many clinical implications. A diverse spectrum of clinical symptoms and signs may manifest as insufficiency of the first ray develops. Morton (2), Lapidus (6), and later Hansen (5) believed that hypermobility of the first ray is a sentinel etiology of many forefoot derangement's such as HAV and lesser metatarsal overload. Hicks (23), in his paper regarding the PA, stated that the PA through an intricate soft-tissue linkage had a profound influence on foot motion with dorsiflexion of the hallux, even in the absence of muscular control. This motion has classically been described as closed kinetic chain plantarflexion of the first ray as well as associated rearfoot supination. This plantar tension created also positions the articulations of the medial column into a more closely aligned position, essentially forming a rigid lever able to withstand ground reactive forces during gait.

The results of our study suggest that as deformity develops in the first ray, functional stability is subsequently lost. The goal in our study was to simulate the dynamic equilibrium which exists between the osseous and soft-tissue constraints of the first ray and the extrinsic forces which antagonize it, most notably ground reactive forces. When feet with HAV deformity were evaluated for functional stability against a vertical force directed at the first ray, a dorsal drift to the first ray was recorded. This occurred due to the first ray's inability to stabilize itself via the windlass mechanism. When specimens were retested after deformity correction, a 26% increase in closed kinetic chain plantarflexion was seen in the first ray.

Two observations can be made from these quantitative observations. The first is that motion in the first ray is largely dependent on first ray position. As deformity develops in the first ray and the alignment is compromised, there is a "damping" of the windlass effect. Second, with correction of the deformity through a simulated proximal osteotomy, there was a restoration of the functional stability via the windlass mechanism which was not previously present in these specimens with HAV deformity. This suggests that a component of measured hypermobility resulting from MPV and HAV is reversible with segmental realignment of the deformity. This increased stability was achieved through proximal realignment of the metatarsal.

It was also seen grossly in this study that as the medial column was stabilized, motion was translated back to the more mobile "essential" joints of the medial column. This concept of essential joints was popularized by Hansen (51) who believes that certain joints are better adapted for motion, while others are not as essential in normal foot function. This suggests that motion as well as functional stability of the first ray are variable, and most likely influenced by many factors. The continuum of first ray hypermobility begins when the metatarsal and hallux diverge and sesamoids drift laterally under the metatarsal head, and ends with complete destabilization and deterioration of the medial column and lesser rays. The question that remains to be answered is how much motion in the first ray is acceptable and how much is pathologic? When the PA and PL are incapable of serving as primary functional stabilizers, subordinate structures such as the ligamentous components of the first ray must play a larger role in stabilization. These structures are far less efficient in maintaining normal anatomic relationships between the components of the first ray. The result is a progressive instability that develops over time. The ray becomes unstable and a point is reached where the first ray is not able to effectively function. The contribution from each individual segment and the factors which influence each individual osseous segment are still not entirely understood. Additionally, the consequence of isolated medial column arthrodesis on first ray mechanics is an area for future investigation.

Our results demonstrate that the sesamoid apparatus plays a significant role in the biomechanical function of the first ray. Less than optimal realignment of the sesamoid apparatus could lead to adverse retrograde forces and contribute to recurrence of the clinical bunion deformity (34, 52). Also, surgical procedures which compromise the function of the sesamoid articulations, such as the classic Keller (53) bunionectomy, could potentially compromise stability in the medial column. Perhaps the first ray insufficiency which results from loss of sesamoid function is a factor in the development of postsurgical sequelae in such operations. First metatarsophalangeal joint implant arthroplasty can also potentially compromise the sesamoid apparatus, and as a result lead to progressive hypermobility in the first ray. Frequently these operations are associated with postoperative symptoms and signs which are similar to a hypermobile first ray.

Lapidus (6) pioneered the operative correction of the bunion deformity with his classic procedure. Later Rutherford (54) improved on this technique with the introduction of internal fixation. Over the past 20 years, the procedure has been refined to accomplish better clinical results (5, 13, 51, 55). Clinically, first ray hypermobility can be qualitatively assessed as increased dorsal excursion to the first ray with a soft end point, call us under the lesser metatarsal heads, as well as osseous hypertrophy of the medial cortical walls of lesser metatarsals, primarily the second metatarsal. Another important clinical assessment advocated by the senior author is the evaluation of first ray motion with forceful dorsiflexion of the hallux in open kinetic chain, enabling the windlass mechanism (56). Astute clinical evaluation of associated foot pathology which could exacerbate first ray hypermobility, such as a tight superficial posterior leg compartment, is also vital. The indications for arthrodesis at the metatarsocuneiform level are still an area of debate. Perhaps with realignment of the ray through a metatarsal osteotomy and distal soft-tissue rebalancing at the metatarsophalangeal joint, the hypermobility in the first ray can be reduced. Conversely, when the secondary constraints of the first ray begin to fail and the structural integrity of the first ray is compromised, an arthrodesis is an option with predictable results. The parameters on which joints of the first ray require arthrodesis to achieve a good result need further definition. The long-term clinical outcomes of different first ray procedures are lacking. Until long-term functional outcomes can be evaluated, the debate over which operative correction is appropriate will continue.

The difficulties in simulating an in vivo situation in a cadaver model are many. Soft tissues begin to degenerate as soon as they are thawed to room temperature. This had implications in our study due to the fact that we relied on an elastic tissue (i.e., PA) for demonstration of functional stability in the first ray. There is also a component of reciprocal uncertainty in any laboratory model. We could not measure motion of the first ray without manipulating it in some way. To observe its unique biomechanical characteristics, we had to alter it by inserting a metatarsal jig, which inevitably alters the behavior of the first ray. Further, it is also very difficult to simulate the loading characteristics of the first ray throughout the gait cycle, which is both complex and highly variable between individuals. Also, it is now clear that the extrinsic muscles of the foot play a very large role in the biomechanical behavior of first ray. The muscles in which the first ray opposes in order to reach a dynamic equilibrium in stance were not evaluated, most importantly the effects of the superficial posterior leg compartment. The goal in our study design was to reduce as many variables as possible in order to isolate those structures specifically being evaluated. By allowing each specimen to reach an equilibrium after being placed in the load frame, each subsequent testing situation could be reliably reproduced. We also were very meticulous regarding soft-tissue dissection and insertion of the metatarsal jig, allowing for both the size of the jig as well as width of the osteotomy. This ensured that the first metatarsal was neither shortened nor lengthened during insertion of the metatarsal jig. Each specimen was thawed, dissected, and tested in one time interval to reduce the amount of tissue degeneration during testing (57). We also conceived that motion would exist during loading of the foot across the metatarsal jig construct regardless of its rigid design. In anticipation of this motion, a radiowave tracking sensor was placed on each side of the jig to record this motion and ensure this motion would not obscure our results.

Insufficiency of the first ray should be considered a continuum with variable clinical symptoms and signs appearing as the first ray becomes more mobile. There is a functional stability created in the first ray via the windlass mechanism, which is dependent on the ability of the foot to engage the PA and create tension which can be used to perform work. Functional deficits in the first ray can lead to dorsal hypermobility and limited motion in the metatarsophalangeal joint (MTPJ), setting the stage for degenerative changes in the joint over time. Lateralizing symptoms can also occur as the first ray fails to support the medial column and weightbearing is shifted to the lesser metatarsals, resulting in MTPJ derangements such as metatarsalgia, capsulitis, and plantar plate pathology. Iatrogenically induced first ray insufficiency from ablative first ray procedures (i.e., implant and resection arthroplasty) results in loss of sesamoid function both in weightbearing and ability to stabilize the first ray via the windlass mechanism. Further excessive shortening of the first ray through aggressive distal decompression osteotomies can result in a "damping effect" on the windlass mechanism and reduce the dynamic stability afforded from this phenomenon. The ability of the foot to engage the windlass mechanism is dependent on a fully corrected first ray which realigns the metatarsal with the sesamoid apparatus and hallux. We were able to show in a cadaver model that functional stability can be increased by 26% with deformity correction without an arthrodesis procedure. As the first ray drifts medially, motion is increased and consequently predisposes the ray to developing a hypermobility syndrome. The PA and the PL are the two primary functional stabilizers of the first ray, and as their important role in stabilization is lost, the foot becomes progressively more symptomatic. Perhaps the hypermobility of the first ray should be conceived of as a syndrome associated with a wide constellation of forefoot symptoms which are subordinate to the first ray deformity. Our study validates the earlier work of Hicks (23, 25, 26) and adds additional insight into the functional stability in the medial column of the foot.

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