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ORIGINAL RESEARCH

Biomechanics of the First Ray. Part III. Consequences of Lapidus Arthrodesis on Peroneus Longus Function: A Three-Dimensional Kinematic Analysis in a Cadaver Model

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It has long been proposed that first metatarsocuneiform joint (FMCJ) arthrodesis, also known as Lapidus arthrodesis, can realign the first ray and permanently lock the FMCJ to control hypermobility. Left unanswered is the functional consequence of peroneus longus (PL) after such a procedure. In this study, the effects of PL on the medial column of the foot before and after metatarsocuneiform arthrodesis were evaluated. Seven fresh-frozen cadaver specimens with an intact foot and ankle were mounted on a custom-made acrylic frame and loaded to 400 N while midstance motor function was simulated with pneumatic actuators. Three-dimensional radiowave tracking transducers were attached to the first metatarsal, medial cuneiform, navicular, and talus to measure osseous movements while tensile loads of 0% to 100% of PL predicted force was applied. Simulated arthrodesis of the metatarsocuneiform joint and then additionally the intercuneiform 1–2 joint was achieved with titanium pins and then retested to determine any change in effect from PL. Significant frontal plane eversion of the medial cuneiform ($p = .016$) and dorsiflexion of the talus ($p = .045$) occurred after Lapidus arthrodesis was achieved. This suggests that arthrodesis at the first metatarsocuneiform joint increases the efficiency of PL stabilizing action on the medial column. (The Journal of Foot & Ankle Surgery 40(3):125–131, 2001)

Key words: first ray hypermobility, Lapidus arthrodesis, peroneus longus

The effects of first ray pathomechanics on the foot as a whole have long been postulated. Morton was the first to recognize the importance of the first metatarsal segment and its role in foot pathology. He described insufficiency of the first metatarsal, a concept he understood as first ray hypermobility (1–5). Others have further investigated the concept of first ray hypermobility, as well as treatments to combat its pathologic consequences (5–16). Nonetheless, influences on first ray biomechanics are complex and further studies may provide a greater understanding.

First Ray Stability

First ray stability with weightbearing load is dependent on both structural and dynamic support. Compromise to any of the supporting mechanisms can lead to a variety of pathologic conditions associated with abnormality of the first ray.

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Structural stability is dependent on the osseous and ligamentous architecture. Some authors believe that an adult human foot with metatarsus primus varus occurs in feet that never fully developed and retains features normally present in the human embryo and lower primates (atavistic) (1–9). The obliquity of the medial cuneiform facet as an atavistic trait has been described as contributing to metatarsus primus varus (5, 7–9). A relatively short first metatarsal segment within the metatarsal parabola has been implicated as contributing to insufficiency of the weightbearing load of the first ray, which in turn leads to first metatarsophalangeal joint pathology, or to lateral forefoot overload (1–5).

Ligamentous support is attributed to the thick plantar first metatarsocuneiform ligament (17, 18) and the plantar fascia (19–21). EMG studies have demonstrated no intrinsic or extrinsic muscular activity acting on the first ray during static stance, inferring that intrinsic ligamentous support is the primary component in maintaining the first metatarsal and medial column stability in static weightbearing (22, 23).

Functional stability of the first ray is dependent on the windlass effect of the plantar aponeurosis and the direct action of peroneus longus in gait. Peroneus longus (PL) is active from midstance through propulsion and inserts on the plantarlateral aspect of the first metatarsal and, to a lesser extent, the medial cuneiform (24–27). The PL has been shown through clinical observation and various studies to function as a plantar flexor of the first ray in the sagittal plane (22, 28–37). Other studies support its role in resisting an adductory force on the first ray and its ability to abduct the forefoot (20, 38). In part I of this series of investigations, it was shown that PL has a significant everting effect during closed kinetic chain in simulated stance phase of gait, locking the first ray into the medial column, thus providing stabilization (39).

The plantar aponeurosis via the windlass mechanism is engaged during heel-off to plantarflex and stabilize the first ray (40–43). In part II of this series of investigations, it was correlated that an increase in the intermetatarsal 1–2 angle leads to a loss in functional stability to the first ray provided by the plantar fascia (43).

First Metatarsocuneiform Joint

Minimal motion occurs in a sound first metatarsocuneiform joint (FMCJ) (12, 18). Increased motion has been shown to occur at this joint when dorsal translation is allowed, or when transection of the plantar ligaments is carried out (16, 18). This joint has been considered primarily as one that is not essential for normal function of the foot as a whole, inasmuch that sacrificing this joint does not lead to further morbidity when addressed appropriately (44).

Many authors have implicated this joint as the crux of deformity inherent to many first ray related conditions, most commonly hypermobility, and its need to be addressed in correcting resulting pathology (1–9, 11, 12, 14, 45–56). Lapidus proposed fusion of the FMCJ for atavistic traits at this joint (7). Since then, with an increasing understanding of first ray pathology and the use of internal fixation, many surgeons have broadened the indications, and evolved the techniques for more predictable and favorable results (6, 11, 44, 46, 49).

It has been proposed that FMCJ arthrodesis can realign the first ray and permanently lock the FMCJ to control hypermobility. Left unanswered is the functional consequence of PL after such a procedure. The purpose of this study is to determine the effect a Lapidus arthrodesis has on the ability of PL to function along the medial column.

Materials and Methods

The materials and methods of this study are similar to that of part I in this series of investigations. The techniques used in these investigations are summarized below.

Specimen Acquisition and Preparation

Seven fresh-frozen cadaver lower limb specimens, transected 15–20 cm above the tibial plafond with intact foot and ankle, were deep frozen to −20°C. There were three females and four males, age ranging from 32 to 87 (mean age, 69). Screening was performed by radiography and visual inspection for abnormal joint space narrowing, significant alignment abnormalities, and osteopenia. Tarsal index was recorded for each specimen as described by Benink (57). Specimens with normal range arch height and without significant pathology were accepted for this study. Before testing, each specimen was thawed to room temperature and all soft tissue was removed from around the leg and dorsum of the medial column, carefully preserving the posterior leg tendons, ligaments, interosseous membrane, and the joints of the foot.

The Load Frame

All specimens were mounted onto a custom loading frame.[4] The frame was made of nonmetallic materials to prevent signal interference of the radiowave tracking system. A downward load was applied through a polycarbonate rod onto the tibia and fibula via a central actuator

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

allowing for near physiologic loading (58). Smaller actuators designed to apply load to tendons through nonmetallic cables surrounded the center actuator. The feet were placed on nonskid material and were allowed to reach equilibrium under load.

Three-Dimensional Tracking System

Receiving transducers from a radiowave tracking system[5] were attached to the first metatarsal, medial cuneiform, navicular, and talus (Fig. 1). This system allows for the osseous segments to be tracked in three dimensions simultaneously in a global coordinate system using 6 degrees of freedom (linear displacement along X, Y, Z coordinates and rotational displacement around each axis). The accuracy of the system was previously determined and verified on a calibrated platform and was determined to be accurate within 0.10 mm and 0.15° for all four sensors (39). Each signal receiver was attached to two carbon fiber rods that were secured to the osseous segments being analyzed; thus the sensor moved with the bone to which it was attached.

Tendon Attachment Clamps

Nonmetallic tendon clamps were custom fabricated and attached to proximal tendon stumps (Fig. 1). These were then connected to pneumatic actuators via nonmetallic cables of braided Dacron® cord.[6] This system allowed for a constant load to be applied to each tendon throughout the testing.

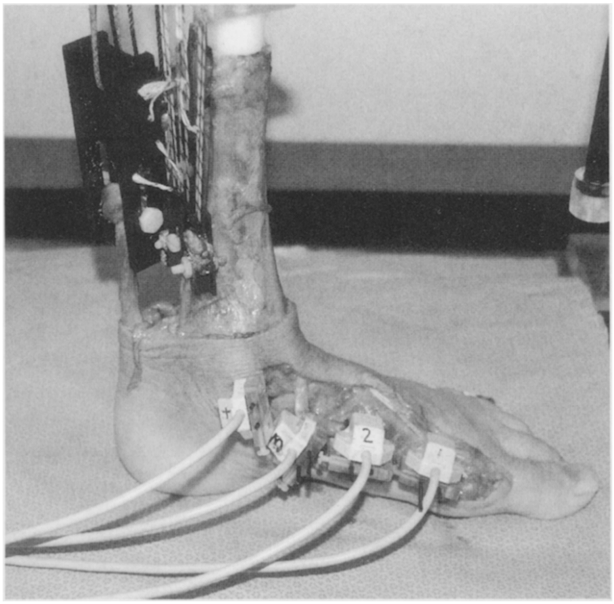

FIGURE 1 Test specimen showing tendon clamps attached to the proximal stumps of the tendons of midstance. Radiowave tracking sensors (numbered) attached to the osseous segments of the medial column.

Determining Tendon Actuator Forces

Relative forces were applied to peroneus longus, peroneus brevis, tibialis posterior, flexor digitorum longus, flexor hallucis longus, and Achilles tendons as determined using Brand's calculation of physiologic cross-sectional area of muscles of midstance (59). From part I of this series, it was determined that 30% of the predicted maximal Achilles load was necessary to maintain consistent balance throughout testing (37). These loads were kept constant for the respective tendons except for PL, which was incrementally increased.

Experimental Sequence

Testing was undertaken at room temperature, keeping the specimens moist with intermittent misting. Each specimen was attached to the frame with the foot at 90° to the leg and loaded to 400 N, while the tendons of midstance were loaded, except for PL. PL tension was then increased from 0% to 50% to 100% of predicted maximal load (39). Three-dimensional data were recorded for the position and orientation of the osseous segments at each load increment (Fig. 1). Test runs were repeated after simulated arthrodesis of the FMCJ, and then after arthrodesis of the FMCJ plus intercuneiform 1–2 joint was performed. Simulated arthrodesis of the FMCJ was achieved by crossing two pins in the sagittal plane with approximately 45 mm of pin engaging bone (Fig. 2A). This is done in a similar fashion with 3.5-mm cortical screws when Lapidus arthrodesis is performed at this institution. Two additional parallel pins in the transverse plane were used to simulate fusion of the intercuneiform joint (Fig. 2B). Parallel pins were used here to eliminate any rotary component in the sagittal plane. Verification of position was achieved with the use of fluoroscopy. Titanium pins were used so as not to interfere with the radiowave tracking system.

Statistical Analysis

Postprocessing of the kinematic data for each specimen was done on a personal computer using a custom software program and a statistics software program.[7] Data were analyzed using a one-way analysis of variance with post

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[5] 3 Space Fastrak®, Polhemus, Inc., McDonnell Douglas Electronics, Colchester, VT.

[6] Western Filament, Inc., Grand Junction, CO.

[7] Statview 4.0, Abacus Systems, Berkely, CA.

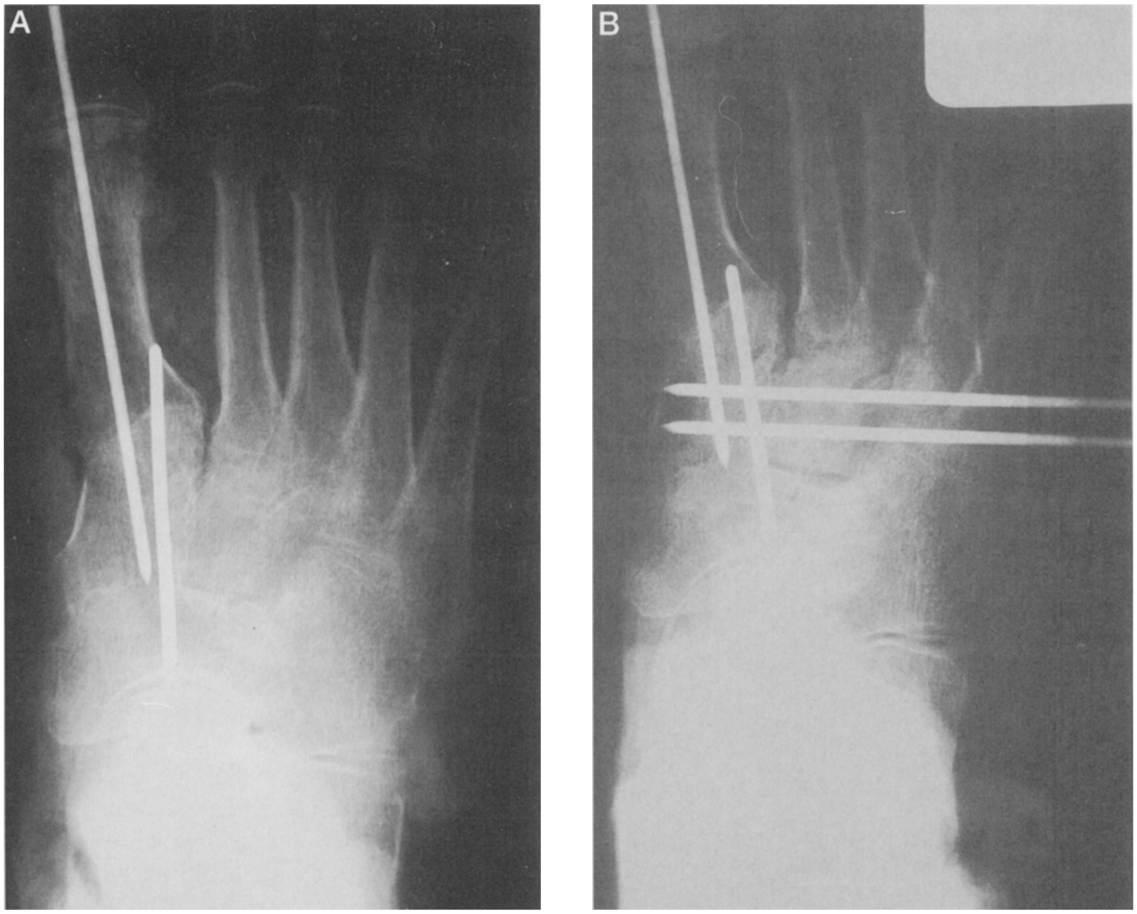

FIGURE 2 *A*, X-ray illustrating crossed titanium pins across the first metatarsocuneiform joint simulating arthrodesis. *B*, X-ray showing parallel pins across the 1–2 intercuneiform joint.

hoc testing using Scheffe's Multiple Comparisons Test for significance at $p < .05$.

Results

Differences between the effect that PL played on the individual osseous motions before and after FMCJ arthrodesis were recorded. Metatarsal motion under the influence of PL showed a slightly increasing trend in the direction of eversion, plantarflexion, and abduction, after simulated FMCJ arthrodesis (0.12°, 0.02°, and 0.11° respectively); however, this was not significant as compared to the intact specimen. After a simulated intercuneiform arthrodesis, there was a slight decreasing trend of these rotations, but this also was not significant.

After FMCJ arthrodesis, rotation of the medial cuneiform was found to be significant for eversion at 0.22° ($p =$ .0161) and abduction at 0.26° ($p = .0249$). An increasing trend of plantarflexion at 0.41° was also seen; however, this was not significant. Additional intercuneiform arthrodesis also showed increasing, but not significant, trends of these respective rotations, but was dampened in comparison with the isolated FMCJ fusion. No significant rotational differences, or consistent trends were noted with navicular motion after arthrodesis was employed. Dorsiflexion of the talus (0.13°) was significant after simulated FMCJ arthrodesis ($p = .045$), but not after intercuneiform fusion. Linear displacements of all osseous segments were negligible, and were not significant after simulated arthrodesis.

Although there was no sensor on the calcaneus to quantify amounts, slight inversion of the heel was noted while loading PL after FMCJ arthrodesis was simulated in most of the specimens. Gross supination with increased arch formation was seen on all specimens after FMCJ arthrodesis.

Discussion

Hypermobility is influenced by a variety of factors both static and dynamic. The pathologic consequences of hypermobility include a variety of clinical signs and symptoms. Functional deficits leading to hypermobility may lead to deformities in the sagittal plane (metatarsus primus elevatus, hallux limitus) or the transverse plane (metatarsus primus varus, hallux abductovalgus) (1–5, 14, 60–62). Failed medial column support can result in lateral forefoot overload with metatarsophalangeal joint capsulitis, plantar plate pathology, metatarsal stress fractures, and degeneration at the lesser metatarsocuneiform joints (44, 62). However, it is not exactly clear what series of events take place in the progression of first ray instability and its resulting complications. Many factors can influence biomechanics of the first ray. No one study can comprehensively incorporate them all. Therefore, it is important to investigate variables independently and determine each individual role.

Part I in this series of investigations found that the most significant action of PL on the medial column was that of frontal plane eversion with most eversion occurring at the first metatarsal, then sequentially less eversion proximally at the medial cuneiform then the navicular (39). As the ligaments between these osseous structures shorten from this torsion action, tightening occurs across these joints, creating a locking mechanism that results in medial column stabilization. This stabilization in turn works in tandem with the plantar fascia, allowing the windlass mechanism to impart its stabilizing function in propulsion (43). Through this action, the PL contributes to first ray stability.

This study demonstrates that with arthrodesis of the FMCJ, function of PL remains intact. The ability of PL to provide eversion and plantarflexion to the first metatarsal was the same, if not slightly greater than before arthrodesis. The amount of eversion seen at the medial cuneiform after fusion was significantly increased. This can be attributed to a coupling effect of the arthrodesis. Thus torsional slack at the FMCJ is eliminated allowing PL to exert its action proximally. The net result is an increased efficiency in PL ability to stabilize and lock the first ray into the medial column. Thus the FMCJ arthrodesis results in enhanced structural stability as well as preserving the functional role of PL in midstance.

Additional arthrodesis at the intercuneiform 1–2 joint, often a necessary procedure for addressing hypermobility when this joint plays a role, resulted in no significant change in enhancing or hindering the effect of PL. The data suggest that this additional fixation still allows PL to function across the naviculocuneiform joint.

Talar dorsiflexion was seen after isolated arthrodesis at the FMCJ. This is most likely a result of PL inability to exert a significant amount of first ray plantarflexion by overcoming ground reactive forces in a closed kinetic chain environment. Rather, the force is transferred proximally to the talus in the form of dorsiflexion (relative first ray plantarflexion). This same phenomenon was also seen in part I with increasing PL pull (39). The longer lever arm achieved following metatarsocuneiform arthrodesis, for which the PL can exert its sagittal plane force, could account for this change seen after the fusion. This could also account for the grossly observed heel inversion, and foot supination following simulated FMCJ arthrodesis.

Although these fusions took place in specimens without apparent deformity, or evidence of first ray hypermobility, it can be postulated that the increased efficiency achieved by PL in specimens with compromise to their first ray stability would be even more significant. However, a study addressing actual correction of such a condition would be needed to evaluate the amount of influence this would have.

There are many procedures that are available to potentially address pathologies of the first ray. Many authors advocate FMCJ arthrodesis when addressing hypermobility (6–9, 11, 12, 14, 45–56). However, this is not universally accepted in the foot and ankle community. Metatarsal osteotomies and addressing the sesamoid apparatus may indeed allow for realignment of plantar fascia and the windlass mechanism, therefore increasing stability (43). However, these procedures may be inadequate if other factors that contribute to instability of the first ray are not addressed. Procedures must address the compromised ligaments about the FMCJ, correct osseous structural deformities, maintain the efficiency of PL function, and allow for realignment of the plantar fascia for which the windless mechanism can further stabilize. FMCJ arthrodesis may potentially address all structural and functional factors contributing to first ray hypermobility.

Extrinsic factors that have contributory roles on the development of first ray hypermobility also need to be addressed. The influence of equinus from a tight superficial posterior muscle group is a powerful destabilizer of the forefoot, and a direct antagonist to PL in midstance. Future research in this area is needed to demonstrate this effect.

While there are obvious limitations to any cadaveric study, such a study can provide information on subtle biomechanics that could not be acquired in an in vivo model. Simulation of muscle function may not be completely accurate, but was based on the most recent physiologic muscle data to date (59). Simulated arthrodesis with pins in cadaveric quality bone will obviously result in some amount of motion compared to a truly fused joint. PL is also active throughout propulsion, but this is difficult to simulate given the complexity of a full gait pattern (24). Special care taken in dissection, preparation, and testing to ensure for integrity of each specimen, and repeat testing of each specimen ensured that this model was mechanically reproducible.

Conclusion

FMCJ arthrodesis increase the efficiency of PL in stabilizing the medial column in closed kinetic chain. Iatrogenic stability of the first metatarsal segment replicates the eversion locking effect created by the PL, allowing PL to exert its action proximally, thereby enhancing stability.

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