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ORIGINAL RESEARCH

Biomechanics of the First Ray. Part IV: The Effect of Selected Medial Column Arthrodeses. A Three-Dimensional Kinematic Analysis in a Cadaver Model

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This study is the fourth in a series of investigations on the biomechanics of the first ray, this part focusing on open kinetic chain range of motion simulating the clinical examination. Segmental sagittal range of motion of the medial column was measured on intact cadaver specimens and compared to various simulated medial column arthrodesis patterns. These arthrodeses included the first metatarsocuneiform, first metatarsocuneiform-intercuneiform, naviculocuneiform, and talonavicular joints. The specimens were mounted to a test apparatus that was comprised of a modified ankle-foot orthosis which held the ankle and rearfoot in fixed neutral position. Additionally, the lesser metatarsus was affixed to the test apparatus while the first ray was left free to be manipulated via a carbon fiber rod attached to a pneumatic actuator. A 24.5-N (5.5-lb) sagittal plane load was applied to the first ray while the specimen was held rigidly in the apparatus. The first ray was manipulated using a repeated measures design. Data were collected for each osseous segment of the medial column using a radiowave tracking system. Kinematic data were collected and statistically analyzed. Results demonstrated in intact specimens that the naviculocuneiform, first metatarsocuneiform, and talonavicular joints contributed an average of 50%, 41%, and 9% of total first ray sagittal plane range of motion, respectively. Furthermore, first ray range of motion was significantly reduced with all of the simulated arthrodeses of the medial column ($p < .05$). These findings suggest that first ray range of motion when evaluated clinically is a blend of motions of joints comprising the medial column. (The Journal of Foot & Ankle Surgery 41(5):278–285, 2002)

Key words: first ray hypermobility, foot biomechanics, isolated arthrodesis

First ray hypermobility has been associated with a wide array of foot pathology. It is often attributed to the first metatarsocuneiform joint (MCJ) and has been linked to hallux valgus, hallux limitus, and lesser metatarsal overload (1–6). Therefore, fusion of this joint for treatment of these symptomatic conditions has been advocated by a number of authors (7–18). Despite the clinical significance associated with first MCJ hypermobility, it remains a poorly defined entity. Clinical evaluation of first ray range of motion (FROM) is often performed in open kinetic chain (OKC) by stabilizing the lesser metatarsals with one hand and taking the first metatarsal through dorsal and plantar flexion range of motion with the opposite hand (11, 12, 14). First ray hypermobility is usually assessed qualitatively as an excess motion of the first ray in the sagittal plane with a soft end point. In addition, other signs of first ray hypermobility such as subsecond metatarsal callus formation and relative thickening of the second metatarsal cortex on radiographic examination

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may support the diagnosis. However, clinical assessment of first ray mobility remains qualitative, making subtle levels of hypermobility difficult to ascertain.

Numerous studies have investigated various aspects of first ray motion. The first ray consists of the first metatarsal and medial cuneiform with a combined axis of motion, allowing dorsiflexion-inversion and plantarflexion-eversion (19). Klaue et al. measured 6.79° (9.3 mm) of OKC first ray dorsal motion in patients with symptomatic hallux valgus versus 3.4° (5.3 mm) in their controls (5). In addition, they calculated the center of rotation of the first ray to be located just distal to the naviculocuneiform joint. This suggested that the observed hypermobility was occurring at the first MCJ; however, motion was not directly measured for each individual joint. Similarly, Ito et al. supported these findings, showing a decrease in the talar–first metatarsal angle in patients with symptomatic hallux valgus, further implicating hypermobility along the first ray, specifically the MCJ (3).

Faber et al. similarly assessed OKC FROM in cadaver feet in both the sagittal and transverse planes (20). They found 3.8° of dorsal displacement of the first metatarsal in the sagittal plane and 2.5° of medial motion in the transverse plane. Additionally, they measured 2.4° of dorsal motion and 2.2° of medial angulation at the first MCJ. They also confirmed a stabilizing effect of peroneus longus on the first ray in the sagittal plane. This stabilizing effect has also been reported in the first of this series of investigations on the first ray (21) and by Bohne et al. (22).

Using a modified Coleman block test to analyze first MCJ motion, mean sagittal plane ROM was found to range between 4.2° and 4.37° (23, 24). However, pure first ray motion is difficult to obtain utilizing this method. Wanivenhaus and Pretterklieber were able to demonstrate dorsiflexion/plantarflexion of the first MCJ in only 9% of cadaveric feet (4.3° mean) (25). They did report 2.6 mm of dorsal displacement in 92% of specimens, but they could not obtain plantar displacement. Ouzounian and Shereff showed 5.0° of sagittal plane motion at the naviculocuneiform joint and 3.5° at the first MCJ in cadaver feet (26).

Generalized hypermobility is often cited as a causative factor in the development of hallux valgus. This concept is supported by an investigation reporting a direct relationship between symptomatic hallux valgus and joint hypermobility, utilizing a hypermobility scoring system (2). A subsequent investigation was unable to demonstrate any correlation between first ray motion and skin stretch and hyperextension of the knee or elbow; however, they did find a positive relationship between hyperflexibility of the thumb and first ray hypermobility (23). In the second in this series of investigations on the first ray, an increased efficiency of the windlass mechanism upon correction of a large intermetatarsal 1–2 angle was demonstrated. This suggests that an inefficient windlass mechanism may exacerbate first ray hypermobility (27).

Other studies have investigated the possible correlation between first ray motion and various anatomic, biomechanical, or congenital factors. Romash et al. demonstrated transverse plane motion of the first MCJ in vivo radiographically (28). In addition, they classified feet based on the amount of articulation between the bases of the first and second metatarsals. Johnson and Kile, utilizing a similar transverse plane stress, concluded that the radiographic appearance of the first MCJ did not correlate with the amount of motion at this joint (4). This observation is supported by several other studies demonstrating no correlation between first MCJ motion and various anatomical factors, such as intermetatarsal 1–2 angle, shape/angle of the distal cuneiform, and height and width of this joint (20, 23, 24). In another anatomical study, Mizel demonstrated the importance of the plantar first MCJ ligament to the stability of this joint (29). He could not demonstrate any MCJ motion in intact specimens; however, 5.9 mm of average dorsal displacement was obtained after sectioning this ligament.

Although normal FROM is thought to be an important clinical factor for asymptomatic locomotion, many questions still remain. While the relative contribution of joints of the medial column has been studied, to our knowledge, no investigation has studied the net effect of isolated medial column arthrodesis on FROM. The purpose of Part IV in this series of investigations on the first ray is to re-evaluate sagittal plane segmental range of motion of the first ray in OKC, simulating the nonweightbearing clinical examination. In addition, this study seeks to determine the relative joint contribution of total FROM as well as the kinematic effects of various medial column arthrodeses on relative arch mobility.

Materials and Methods

Six fresh-frozen left cadaver lower limb specimens were obtained from the Department of Biological Services at the University of Washington. All specimens had intact feet and ankles. All specimens were without visible foot deformity. The specimens were deep-frozen to −20°C. Each foot was thawed at room temperature immediately prior to preparation and testing. Prior to testing, all of the feet were screened for joint limitations, evidence of previous trauma, and pre-existing arthritic conditions. No specimens were excluded from the study. In addition, measurements were performed on AP radiographs for each specimen to determine the hallux valgus and intermetatarsal 1–2 angle utilizing standard methods. The skin and soft tissues were then removed to create osteoligamentous preparations. Care was taken to preserve the ligaments and joint capsules. Each specimen was placed into a custom-fabricated mounting apparatus consisting of a specially modified polypropylene ankle-foot orthosis (AFO) to accommodate left feet. This AFO was fixed on a platform and modified at its medial extent to allow for unrestricted FROM. Each foot was rigidly secured to this AFO with nonmetallic fasteners, holding the subtalar and ankle joint in their respective neutral positions (Fig. 1). This configuration allowed adequate stabilization of all specimens to the testing apparatus without any significant motion between the cadaver and the AFO. This was confirmed by tracking talar motion. Both the lesser metatarsus and the rearfoot were immobilized in the test apparatus, leaving the first ray free to be manipulated in the sagittal plane.

The specimen and test platform were placed into a custom acrylic load frame.[4] A bi-directional pneumatic load cylinder, located at the top of the load frame, was attached via a carbon fiber rod to the first metatarsal. This rod was attached to the first metatarsal with a nylon fastener which was secured to the proximal aspect of the first metatarsal head both plantarly and dorsally. Special care was utilized to avoid applying any tension or disrupting the plantar fascia when securing the load actuator rod.

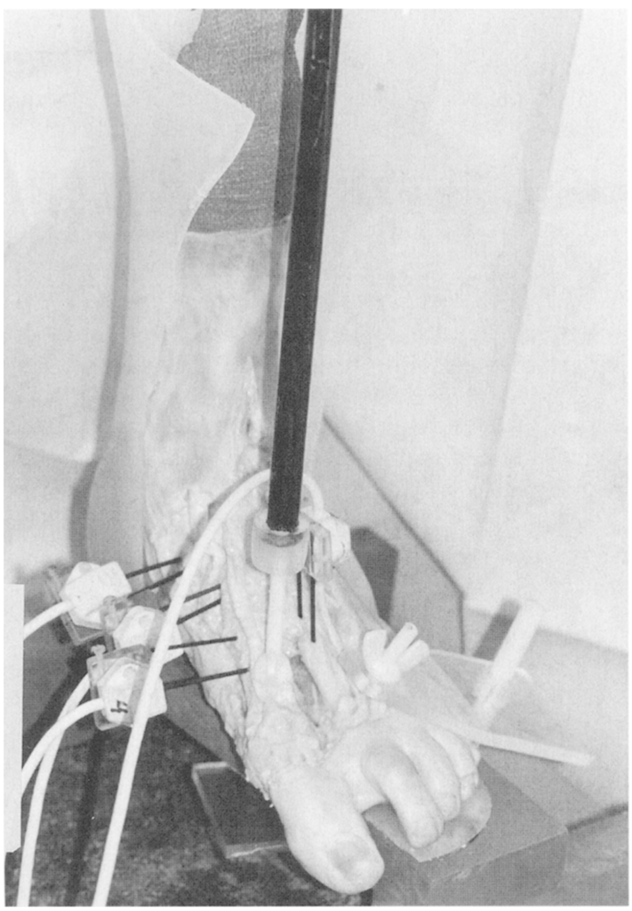

FIGURE 1 Cadaver specimen mounted in the custom-modified AFO with sensors attached to osseous segments and the pneumatic cylinder attached to the first metatarsal via the carbon fiber rod.

Three-Dimensional Tracking System

Five osseous segments were tracked with a radiowave tracking system.[5] These segments included the first metatarsal, second metatarsal, medial cuneiform, navicular, and talus. Each tracking sensor was attached to the corresponding bone with two carbon fiber rods (Fig. 2). Radiowave signals were collected and the position of each sensor was determined with the aid of computer algorithms, which convert these signals to data points. This system was tested and determined to be within 0.10 mm and 0.15° for all receivers. The Fastrack® system tracks motion in a global coordinate system with 6 degrees of freedom (linear displacements along X, Y, and Z coordinates and rotation around each axis).

Testing Protocol

After being secured in the AFO with sensors attached to each corresponding osseous segment, each specimen was taken through the testing sequence. First, the neutral position of the first ray was determined and defined when the plantar aspect of the sesamoids was on the plane of the lesser metatarsals. This was achieved by lightly loading the plantar forefoot on a flat surface and maintaining the first ray position with a 0.062-inch titanium Kirschner wire between the first and second metatarsals. Data were collected for this neutral position and used for reference to interpret subsequent data points. A 24.5-N sagittal plane force was exerted on the first metatarsal head via the pneumatic actuator. This amount of force was determined to be ideal during preliminary testing. It allowed full, reproducible sagittal plane excursion of the first ray while minimizing the effects of soft-tissue creep. The first ray was taken through both dorsal and plantarflexion with data collection at each end point.

This sequence of data collection was repeated after various simulated medial column fusions: first MCJ, first MCJ combined with intercuneiform 1–2 joint (ICJ), naviculocuneiform joint (NCJ), and talonavicular joint

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

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

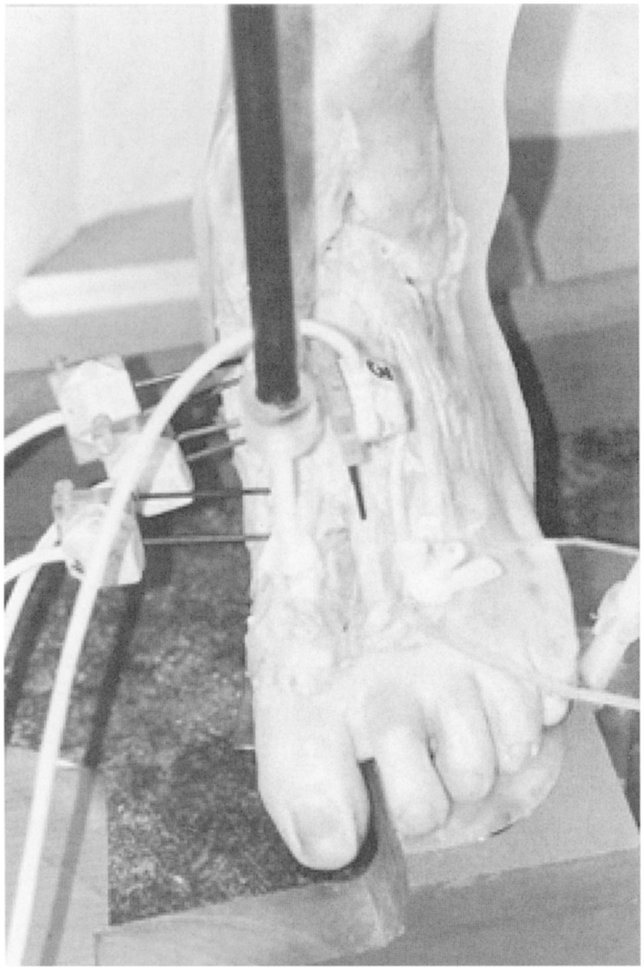

FIGURE 2 Cadaver specimen secured to the custom-fabricated mounting apparatus. Note the attachment of the radiowave tracking sensors to each osseous segment with two small carbon fiber pins.

(TNJ). Each fusion was performed with multiple titanium Kirshner wires to prevent interference with the tracking system. Simulated fusion was verified kinematically with the radiowave tracking system. Data were collected for the first ray neutral position, dorsiflexion, and plantarflexion. The testing sequence was randomized for each specimen to minimize the cumulative viscoelastic effects.

Statistical Analysis

After collection, data were processed utilizing a custom software program and were then analyzed with a statistics software program.[6] These data were assessed with repeated measures analysis of variance (ANOVA). Analysis to compare motion along each of the osseous segments of the first ray was also performed, to measure the effect of simulated arthrodesis. Statistical significance was represented by $p < .05$.

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

Results

First Ray Range of Motion and Individual Joint Contribution

The average hallux valgus and intermetatarsal 1–2 angles for the six specimens in this study were 8.4° (range, 6°–12°) and 7.0° (range, 4°–10°), respectively. The contribution of each individual joint to OKC first ray ROM is summarized in Table 1. The average FROM was 6.38° ± 0.46°. By subtracting motion between various osseous segments, range of motion at the individual articulations could be calculated. Based on these calculated ranges of motion, the NCJ demonstrated the most motion with an average of 3.20° ± 1.21°. This represented 50% of total FROM. Motion at the first MCJ averaged 2.64° ± 0.89° and TNJ motion averaged 0.53° ± 0.34°. This represented 41% and 9% of total FROM, respectively (Fig. 3). Although the NCJ demonstrated approximately 18% more motion than the MCJ, this difference did not reach statistical significance ($p = .53$). Range of motion for both the MCJ and NCJ was significantly larger than that for the TNJ ($p < .05$). When average dorsiflexion motion was compared to plantarflexion, there was no statistically significant difference for each osseous segment.

Effect of Simulated Arthrodeses on First Ray Range of Motion

The effects of selected arthrodesis procedures on overall FROM are summarized in Table 2. All simulated fusions were found to have a statistically significant impact on FROM ($p < .05$). Arthrodesis of the MCJ/ICJ resulted in the largest decrease in first ray motion (Fig. 4). This effect was statistically significant when compared with MCJ fusion alone ($p = .024$) and TNJ fusion ($p = .0031$); however, comparison with NCJ fusion revealed no statistical significance ($p = .18$). There was also a significant difference when comparing MCJ and NCJ fusion

TABLE 1 Average first ray ROM and individual joint contribution

	First Ray	MCJ	NCJ	TNJ
ROM (degrees)	6.38	2.64	3.20	0.53
Standard deviation	0.46	0.89	1.21	0.34
Percent of total ROM		41%	50%	9%

MCJ, metatarsocuneiform joint; NCJ, naviculocuneiform joint; TNJ, talonavicular joint.

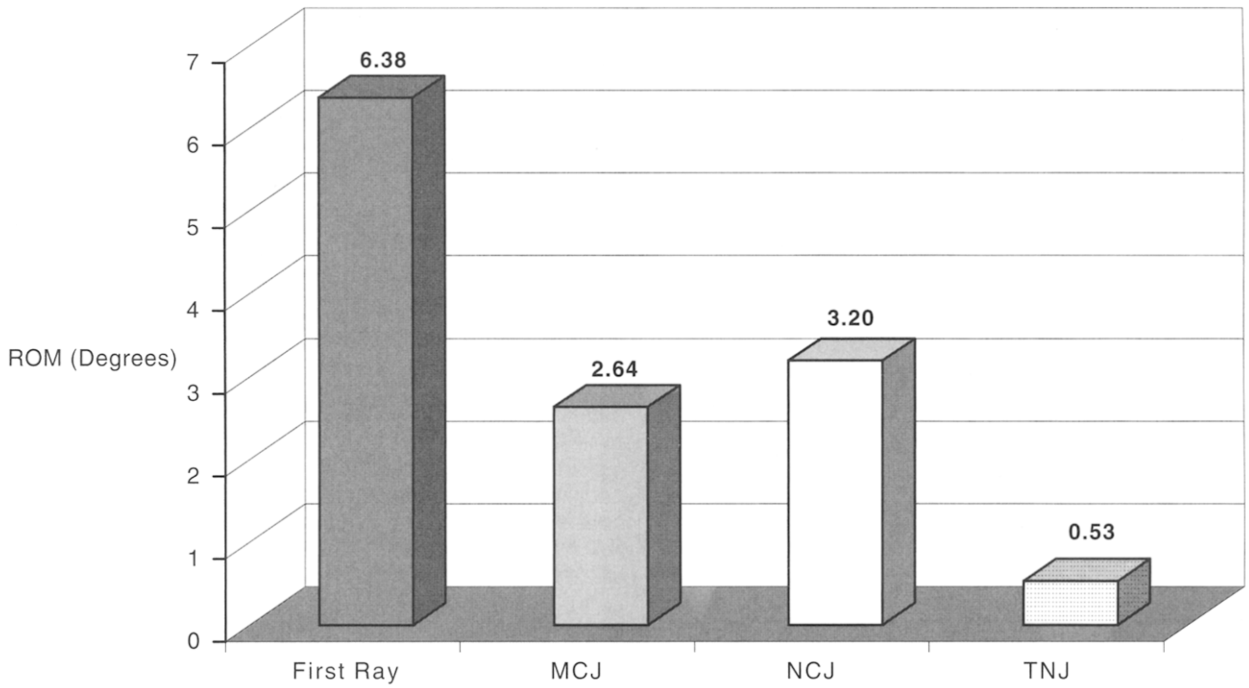

FIGURE 3 Average ROM of the first ray. Sagittal plane ROM of the first metatarsal (first ray), first metatarsocuneiform joint (MCJ), naviculocuneiform joint (NCJ), and talonavicular joint (TNJ) in open kinetic chain.

versus TNJ ($p = .0088$ and .030). The difference between NCJ and MCJ or MCJ/ICJ was not significant ($p = .95$ and .18).

The effects of the various simulated arthrodesis procedures on the motion at the other joints are summarized in Tables 3 and 4. First MCJ motion increased with both NCJ and TNJ fusion (18% and 3%); however, neither of these changes was statistically significant ($p = .45$ and .87). The effect of different arthrodeses on NCJ range of motion showed variable results. NCJ motion was noted to increase 2% with MCJ fusion ($p = .88$). Conversely, NCJ range of motion decreased with both MCJ/ICJ (16%) and TNJ fusions (12%). Both of these effects were not significant ($p = .47$ and .43). When comparing the impact of NCJ and TNJ fusion on MCJ range of motion, there was no statistical significance ($p = .29$). Comparison of MCJ versus MCJ/ICJ arthrodesis on NCJ range of motion also was not significant ($p = .16$), even though these two fusions had opposite effects on the NCJ ROM. Also, the effects of MCJ and MCJ/ICJ fusions versus TNJ on NCJ motion were not significantly different ($p = .15$ and .72, respectively).

TABLE 2 Effects of selected medial column arthrodeses on first ray ROM

	No Fusion	MCJ	MCJ/ICJ	NCJ	TNJ
First Ray ROM (degrees)	6.38	4.00	3.50	3.81	5.53
Standard deviation	0.46	0.57	0.55	0.96	0.75
Percent decrease		37%	45%	40%	13%
p Value		.0001	.0003	.0045	.0325

MCJ, metatarsocuneiform joint fusion; MCJ/ICJ, metatarsocuneiform joint fusion combined with intercuneiform 1–2 fusion; NCJ, naviculocuneiform joint fusion; TNJ, talonavicular joint fusion.

TABLE 3 Effect of selected medial column arthrodeses on MCJ ROM

	Free	NC	TN
MCJ ROM (degrees)	2.64	3.11	2.72
Standard deviation	0.89	1.14	0.88
Percentage change		18% ↑	3% ↑
p Value		.45	.87

MCJ, metatarsocuneiform joint; Free, no arthrodesis; NC, naviculocuneiform arthrodesis; TN, talonavicular arthrodesis.

TABLE 4 Effects of selected medial column arthrodeses on NCJ ROM

	Free	MC	MC/IC	TN
NCJ ROM (degrees)	3.20	3.27	2.69	2.81
Standard deviation	1.21	0.70	0.52	0.59
Percentage change		2% ↑	16% ↓	12% ↓
p Value		.88	.47	.43

NCJ, naviculocuneiform joint; Free, no fusions; MC, metatarsocuneiform arthrodesis; MC/IC, metatarsocuneiform arthrodesis combined with intercuneiform 1–2 arthrodesis; TN, talonavicular arthrodesis.

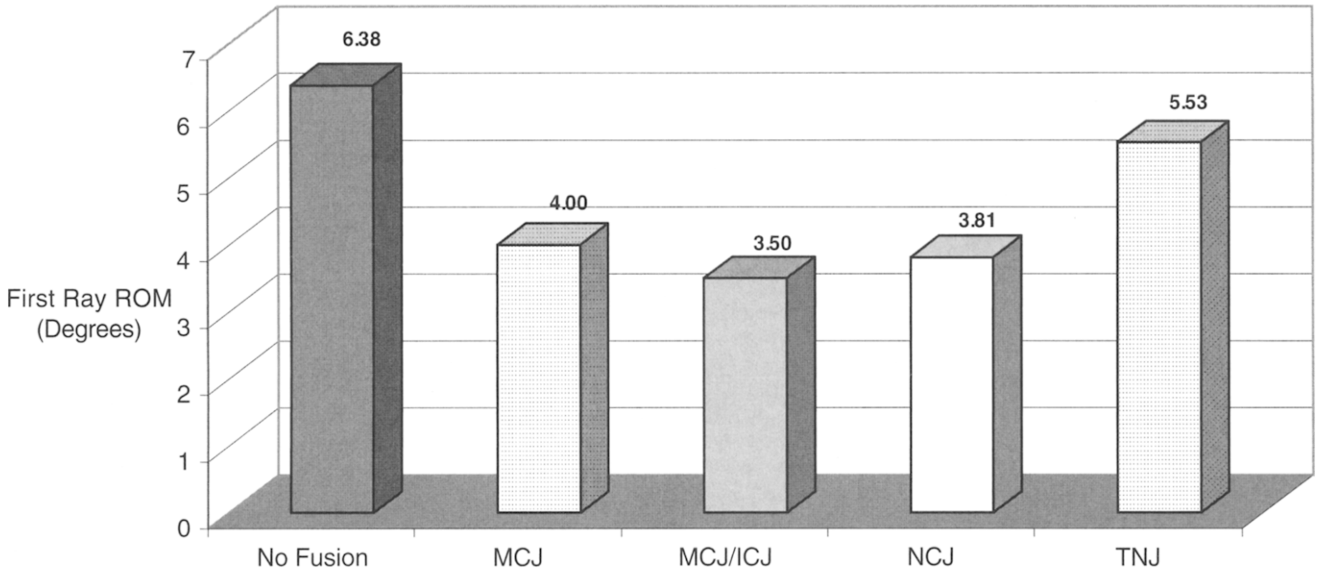

FIGURE 4 Effects of selected medial column fusions on first ray ROM. Average OKC ROM of the first ray before and after simulated arthrodesis of the first metatarsocuneiform joint (MCJ), first metatarsocuneiform joint combined with intercuneiform 1–2 joint (MCJ/ICJ), naviculocuneiform joint (NCJ), and talonavicular joint (TNJ).

Discussion

Hypermobility of the first ray is generally thought to be an important etiologic variable in the development of hallux valgus. Although it has received significant attention, first ray hypermobility remains poorly defined and at best a qualitative assessment clinically. In fact, there are variable reports in the literature with respect to FROM and motion at the individual joints of the medial column (5, 23–26). Many of these studies employed different techniques and methodologies, which makes it difficult to interpret data among these different investigations.

In the current study, OKC first ray ROM was determined in cadaver specimens, simulating the nonweightbearing clinical examination. Also, motion was determined for the individual medial column joints. The overall ROM reported here is similar to that of Klaue et al. (5) in their controls; however, their reported ROM for feet with symptomatic hallux valgus was greater.

Relative contribution to range of motion of the various joints along the medial column was determined in this investigation and compared well to results reported by Faber (20). The results confirm that the NCJ is a major contributor to FROM along with the MCJ. Faber found 57% of first ray motion occurred at the first MCJ, 35% at the NCJ, and 8% at the TNJ. The present study demonstrated that approximately 41% of first ray ROM occurs at the MCJ, 50% at the NCJ, and 9% at the TNJ. The percentages are similar; however, the relative contribution of the MCJ versus the NCJ is reversed. This may be because Faber utilized specimens with hallux valgus, whereas in this investigation, no specimens were noted to have deformity. Moreover, this helps to support the theory that hallux valgus may be caused by hypermobility at the MCJ.

The second part of this study examined the effects of various medial column fusions on FROM. Our results demonstrate that all of the medial column fusions tested had a significant dampening effect on first ray motion. Also, arthrodesis of the first MCJ combined with intercuneiform fusion limits first ray motion to a greater extent than other isolated medial column fusions. This effect was more pronounced than either isolated MCJ or NCJ fusion. This difference was statistically significant when comparing this combined fusion with MCJ fusion alone. This increased effect of combined MCJ and ICJ arthrodesis may be explained by a possible partial locking of the NCJ through the ICJ fusion. This is demonstrated by the fact that NCJ range of motion was noted to decrease with this combined fusion, whereas it increased slightly with an isolated MCJ fusion. Therefore, in hallux valgus feet with severe hypermobility, an ICJ arthrodesis may be of significant benefit in controlling this excess motion.

The observation that none of the simulated medial column fusions altered motion at the other joints to any significant degree is an interesting one. This is especially true for the effect of isolated MCJ arthrodesis on motion occurring at the NCJ. These findings lend support to Hansen's theory that these joints may not be essential joints to normal foot function (S. T. Hansen, personal communication, 1999). In addition, the results here counter the idea that the first MCJ fusion may deleteriously affect first ray biomechanics, causing undue stress on the adjacent joints, leading to possible early arthrosis (30). Furthermore, the observations of this and other studies support the theory that symptomatic hallux valgus is associated with hypermobility occurring at the first MCJ (20). Therefore, fusion of this joint for treatment of hallux valgus addresses this abnormal motion, thereby improving first ray biomechanics.

One potential limitation of this study is that it is a cadaveric investigation. In order to limit soft-tissue degeneration in the specimens, each cadaver was thawed, prepared, and tested in one setting. In addition, the sequence of testing was randomized for each specimen to reduce the impact of soft-tissue viscoelastic effects. Another related shortcoming is that the fusions were simulated. To verify absence of motion at the simulated arthrodesis, data were collected across each fusion site. The minimal motion occurring across these fusions and the degree of motion were determined to be insignificant. Even though this study was not in vivo, relative joint motion was assessed here and each specimen served as its own control with respect to the effect of the fusions. Furthermore, it would be technically difficult to measure accurately this segmental motion in vivo and it would be impossible to assess the impact of simulated fusions on the biomechanics of the first ray.

Future investigation is warranted in evaluating isolated arthrodesis of the medial column with feet with hallux valgus deformity. Both open and closed kinetic chain models need to be investigated to help better understand the concept of first ray hypermobility.

This study was a biomechanical investigation of the first ray. Normal first ray motion with simulation of the clinical open kinetic chain examination is reported here. In addition, the individual joint contribution to this motion is presented, as well as the effect of various simulated arthrodeses on first ray motion. Although this study provides some further insight into first ray biomechanics, questions remain. This investigation does not directly address or answer the question of hypermobility; however, when viewed in relationship to other studies (5, 20), it does appear that hallux valgus is associated with hypermobility at the MCJ. This investigation suggests that isolated arthrodesis at the NCJ and MCJ will significantly reduce first ray mobility. It is likely that this concept developed on this cadaver model can be used in the clinical treatment of mechanical deficiencies of the first ray.

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