First Metatarsophalangeal Joint Arthrodesis: Quantitative Mechanical Testing of Six-Hole Dorsal Plate Versus Crossed Screw Fixation in Cadaveric Specimens

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Quantitative strength analysis of first metatarsophalangeal joint arthrodesis was performed using two fixation techniques: a small 6-hole plate with an interfragmentary screw or two crossed lag screws. Twelve matched-pair fresh-frozen cadaveric specimens (24 trials) were used for direct comparison of each of the two fixation techniques. All joint surfaces were prepared with power conical reamers utilizing a standard technique. The fixation construct was stressed to failure on each specimen using a computer-integrated materials tester. Fixation stiffness defined as force (load) over displacement and point of ultimate failure was evaluated. The six-hole plate and interfragmentary screw fixation method was a statistically stiffer form of fixation ($p > .01$) and displayed a greater point of ultimate failure ($p > .002$) under the laboratory conditions. (The Journal of Foot & Ankle Surgery 40(4):208–213, 2001)

Key words: first metatarsophalangeal joint arthrodesis, mechanical testing

Clutton first described first metatarsophalangeal (MTP) joint arthrodesis in 1894 and since then various methods and techniques for fixation have been described in the literature (1–30). Arthrodesis of the first MTP joint is indicated for a variety of pathologies, including severe hallux valgus, hallux rigidus, deformity secondary to rheumatoid arthritis, previously failed joint procedure, traumatic arthritis, and neuromuscular instability.

Coughlin developed a technique for first MTP joint fusion in 1990, utilizing power cannulated reamers to prepare convex-concave joint surfaces and reported a 100% success rate using a Kirschner wire (K-wire) and a dorsal mini-fragment compression plate for fixation (13). In 1994, Coughlin and Abdo used a low-profile mandibular plate with convex-concave joint surface preparation and reported a 98% successful fusion rate (14). Curtis et al. compared various fixation techniques with two methods of joint surface preparation for first MTP joint arthrodesis: planar resection and convex-concave power conical reaming of the joint surfaces (26). They demonstrated that the surfaces prepared with convex-concave reaming in combination with a single lag screw produced a more stable fixation than planar resection with K-wires, lag screws, or a dorsal plate and screws. They concluded that the increased stability was due to the greater surface contact at the fusion site as well as the inherent stability of the overlapping convex-concave joint surfaces (26).

Sage et al. published their series of nine patients (12 feet) who underwent first MTP joint arthrodesis utilizing Coughlin's technique (18). The authors reported a 100% fusion rate without casting, with an average follow-up time of 6.9 months. The joints were fused using the Small Joint Reamer System[4] and utilized a dorsal plate with single interfragmentary lag screw or two crossed lag screws for rigid internal fixation (Fig. 1). Immediate postoperative weightbearing was allowed in a surgical shoe with a walker or crutches. Patients were subsequently advanced into a soft athletic shoe in 3–4 weeks. They concluded the technique was effective in achieving first

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[4] Howmedica Inc., Rutherford, NJ.

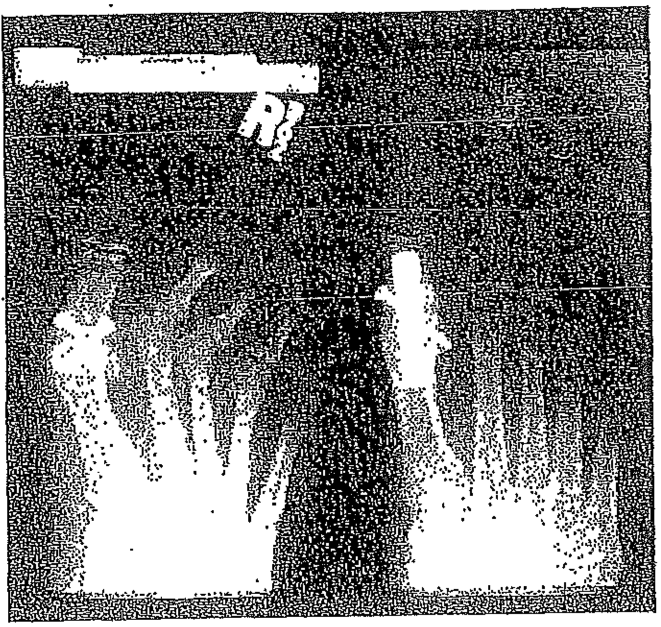

FIGURE 1 Radiographic examples of the two fixation methods tested during this study. These represent actual postoperative patient radiographs, not study trials. *Left*, two crossed screws. *Right*, six-hole dorsal plate with a single interfragmentary screw.

MTP joint fusion, and may serve as a primary procedure for first MTP joint pathology (18).

Numerous methods of fixation have been reported since 1950. Examples include K-wires, Steinmann pins, screws, plates, compression clamps, staples, wires, and sutures (1–10, 12–30). It was hypothesized for this study that the dorsal plate and screws would be a statistically stronger form of fixation than crossed screws. Therefore, the purpose of this study in a reamed model was to compare the stability between two types of internal fixation: six-hole dorsal plate with a single interfragmentary lag screw and two crossed lag screws, in cadaver specimens in a matched-pair design.

Materials and Methods

Twelve matched pairs (24 feet) from fresh-frozen cadaver specimens were utilized for the trials. There were eight male and four female specimens with an average age of 69.8 years (range 51–95 years). The specimens were sealed in freezer bags and stored at −20°C until the day of testing. The sealed specimens were thawed in warm water and room air. After the specimens were fully thawed, all soft tissue was dissected from the first metatarsal and proximal phalanx. The experiments were performed on each matched pair on the same given day. None of the specimens displayed evidence of previous foot surgery or trauma upon dissection.

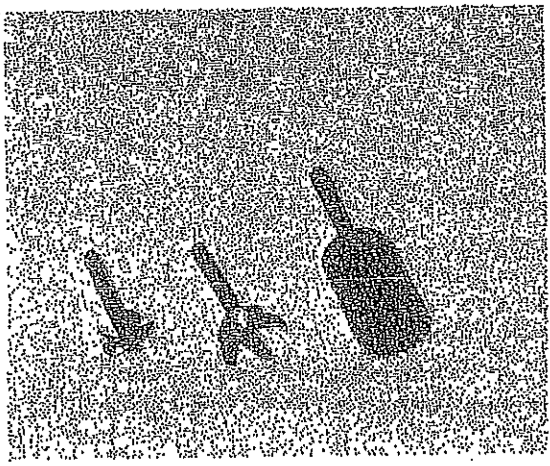

FIGURE 2 The Small Joint Reamer System (Howmedica). From *left* to *right*: convex phalangeal reamer, concave metatarsal reamer, and metatarsal barrel reamer.

The Small Joint Reamer System (Fig. 2), Luhr Vitallium Alloy six-hole plates, and Luhr 2.7-mm self-tapping cortical screws were used to prepare and fixate the MTP joints. The articular cartilage was resected with a cut perpendicular to the respective shaft of the first metatarsal and phalanx with a power saw. A 0.062-inch K-wire was driven centrally into the medullary canal of the metatarsal approximately 1.5 cm. A cannulated barrel reamer was used to create a cylinder of constant dimension from the metatarsal head. Excess bone was removed using a rongeur. The concave metatarsal cannulated power reamer was used to produce a convex surface. The guide K-wire was removed from the metatarsal and driven centrally into the proximal phalanx approximately 1.5 cm. Next, the convex phalangeal reamer was used to fashion a concave surface from the base of the proximal phalanx. The same technique was repeated for each matched-pair specimen by the same surgeon (D.J.B.).

The base of each metatarsal was potted in a metal holding device with polymethylmethacrylate (PMMA) bone cement. A goniometer was used to align the MTP joint in 20° dorsiflexion and 15° abduction in relation to the long axes of the shafts of the first metatarsal and proximal phalanx. This position was manually compressed while temporary fixation was applied. Temporary fixation was either a 0.062-inch K-wire or a Luhr 2.0-mm drill bit placed from distal medial to proximal lateral across the MTP joint. The same investigator (D.J.B.) positioned each specimen; the alignment was reconfirmed after temporary fixation was applied.

In one specimen of the matched pair, a six-hole plate was applied to the dorsal surface of the MTP joint. The Luhr plate was prebent to 20° to contour the dorsal surface of the MTP joint. Six Luhr 2.7-mm self-tapping cortical screws were applied, three on each side of the joint. The central holes were eccentrically drilled. The temporary fixation applied across the MTP joint was removed and replaced with an appropriate length 2.7-mm cortical screw in lag technique (Fig. 3).

In the accompanying matched-pair specimen, a Luhr 2.0-mm drill was passed from distal lateral to proximal medial after temporary fixation was applied. After over-drilling the proximal cortex with a 2.7-mm drill, a Luhr 2.7-mm cortical screw was inserted in lag fashion. The temporary fixation was removed and replaced with a second appropriate length screw in a lag fashion (Fig. 4).

A computer-integrated Instron®[5] materials testing machine (model 1122) was used to apply a force necessary to produce the ultimate load failure. A linear variable differential transducer (LVDT)[6] was used to measure displacement across the MTP joint while the load was applied. In addition, the LVDT was used to determine the stiffness of the fixation. The resolution of the LVDT is approximately 1 μm with a range of +/−5 mm. An IBM-compatible 486 computer via an analog to digital board[7] translated force versus displacement data.

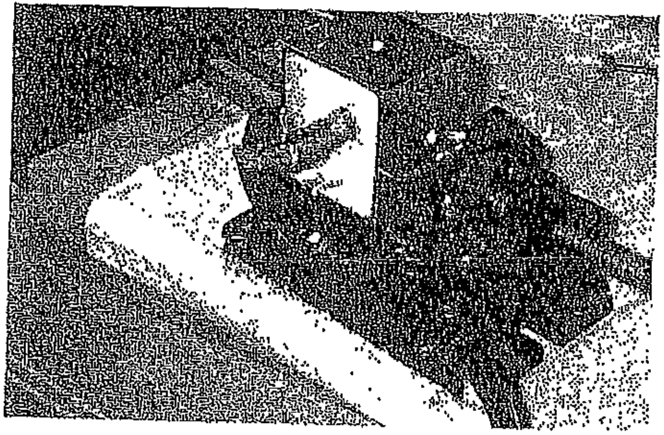

FIGURE 3 An example specimen used in the study. First metatarsophalangeal arthrodesis fixated with a six-hole dorsal plate and a single interfragmentary screw potted in PMMA bone cement.

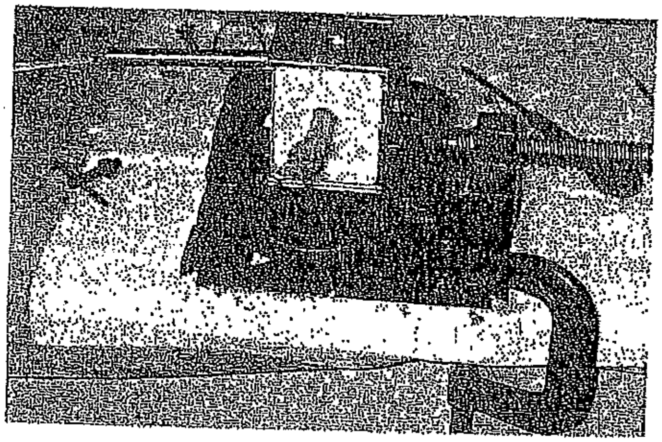

FIGURE 4 An example specimen used in the study. First metatarsophalangeal arthrodesis fixated with two crossed screws potted in PMMA bone cement.

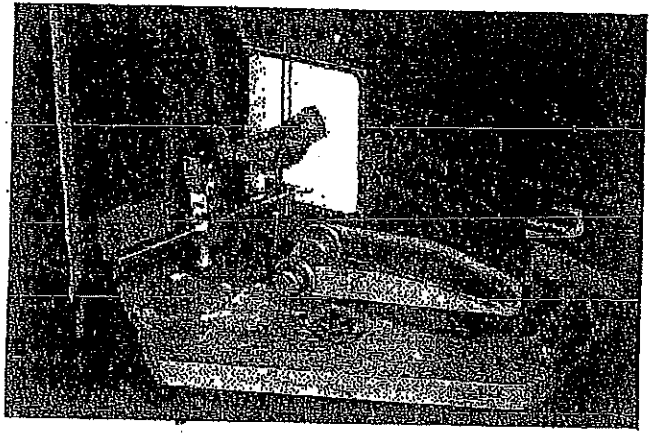

FIGURE 5 An sample specimen secured in the vice on the Instron materials testing machine. Note the LVDT is mounted on the plantar aspect of the proximal phalanx and the receiving plate is mounted on the first metatarsal. Also note the wire cable around the proximal phalanx used to apply a dorsally directed load.

The PMMA-potted matched-pair specimens were secured with a vice on the Instron machine. The LVDT was mounted to the proximal phalanx utilizing a holding device and the receiving plate was fixated to the PMMA-potted first metatarsal (Fig. 5). Thus, the first metatarsal served as a stable reference point relative to the proximal phalanx that held the LVDT transducer. The loading force was applied to the proximal phalanx and the displacement across the first MTP joint was measured. The LVDTs were applied in the same fashion to each specimen by a single investigator (D.J.B.).

Affixed to the Instron was a testing jig that consisted of a looped wire cable at the free end. The loop encircled the proximal phalanx (Fig. 5) and a 2.7-mm screw was inserted on the plantar aspect of the phalanx, 12 mm distal to the MTP joint. This served to prevent the cable from sliding distally during load testing. The Instron machine applied a constant vertical force to the plantar aspect of the proximal phalanx at the rate of 2 mm/min. The LVDT measured the displacement across the MTP joint as a result of the load placed by the Instron testing machine across the joint.

All tested specimens demonstrated rigid bone contact and stability upon gentle manual manipulation. Force and displacement data was collected by the computer and translated to the analog to digital board. The data were collected at 100 cycles per second (Hertz). Each specimen was loaded until the point of ultimate failure. The

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[5] Instron, Inc., Canton, MA, model 1122.
[6] Sensotec, Columbus, OH, model S5, Ultra Precision.
[7] Data Translation Inc., Marlboro, MA, model 2821G.

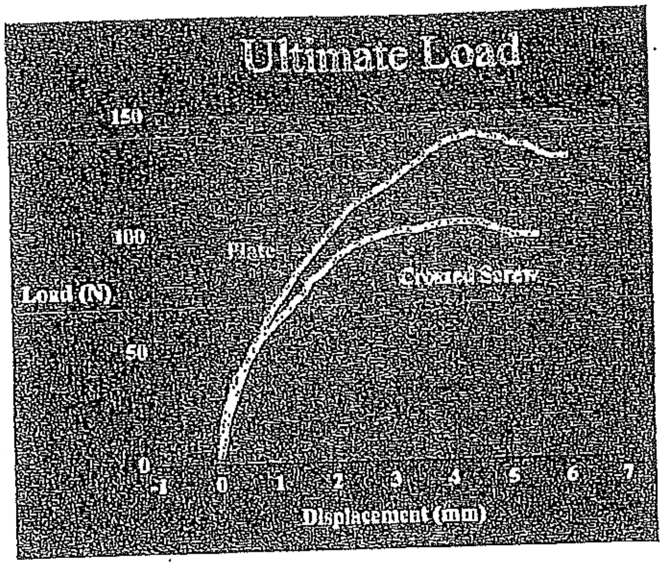

FIGURE 6 Ultimate load graph from specimen D31667. The six-hole plate with a single interfragmentary screw had an ultimate load failure of 141 N. The two crossed screws had an ultimate load failure of 103 N.

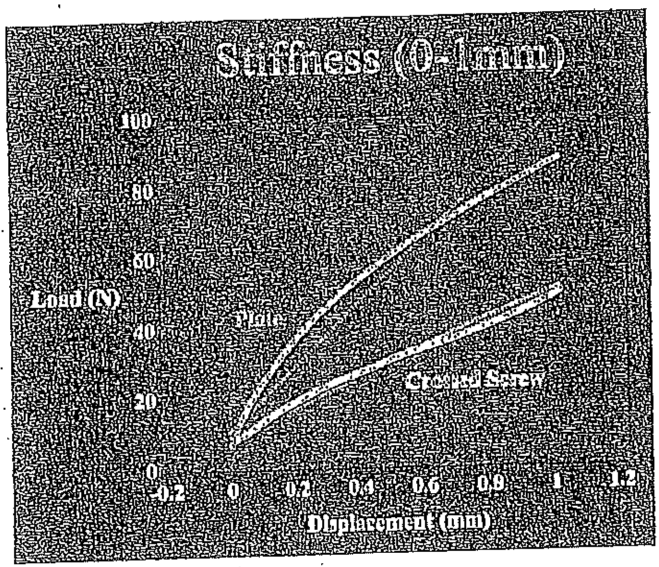

FIGURE 7 Stiffness (load/displacement) from 0 to 1 mm of displacement graph from specimen D31509. The six-hole plate with a single interfragmentary screw was statistically stiffer during 0–1 mm of displacement than the two crossed screws.

ultimate load to failure of each fixation system was identified graphically by determining the point at which the linear progression of applied force peaked and then fell off (Fig. 6). Internal fixation stiffness, defined as force in Newtons ($kg.m/s^2$) over displacement in millimeters, was evaluated between 0–1 mm and 1–2 mm of displacement (Fig. 7). The internal fixation stiffness was also determined at the point of ultimate failure. Stiffness for each fixation technique was quantified utilizing the paired *t*-test.

TABLE 1 Stiffness (Newtons/mm) 0 to 1.0 mm displacement

	Mean	Range	S.D.
Plate/screw	121 N/mm	43–233	56
Crossed screws	72 N/mm	6–113	33
t-Test	$p < .01$*		

TABLE 2 Stiffness (Newtons/mm) 1.0 to 2.0 mm displacement

	Mean	Range	S.D.
Plate/screw	37 N/mm	23–59	10
Crossed screws	31 N/mm	5–56	16
t-Test	$p < .09$		

TABLE 3 Ultimate load to failure (Newtons)

	Mean	Range	S.D.
Plate/screw	180 N	71–275	58
Crossed screws	130 N	22–246	64
t-Test	$p < .002$*		

*Statistically significant.

Two matched pairs were disregarded due to poor bone quality and not included in the experiment. The power reamers destroyed the bone and the attempts at fixation were not possible. As a result, the experiment consisted of 12 matched pairs.

Results

Table 1 summarizes data on displacement between the first metatarsal and proximal phalanx from 0 to 1 mm. The six-hole plate with a single interfragmentary screw was statistically stiffer from 0 to 1 mm of displacement ($p < .01$) than the two crossed screws (mean, 121 N/mm). The mean stiffness from 0 to 1 mm for the crossed screws was 72 N/mm.

Table 2 summarizes data on displacement between the first metatarsal and proximal phalanx from 1-2 mm. There was no significant difference in stiffness between the two different fixation techniques from 1-2 mm of displacement ($p < .09$) (Table 2). The mean stiffness between 1 and 2 mm of displacement for the dorsal plate and screws versus the crossed screws was 37 N/mm and 31 N/mm, respectively.

Ultimate load to failure was also compared utilizing the paired *t*-test and summarized in Table 3. The six-hole plate and interfragmentary screw was a statistically stiffer ($p < .002$) than the two crossed screws at the point of ultimate failure (mean, 180 N/mm). The mean ultimate load to failure for the crossed screws was 130 N/mm. The specimens were observed during loading and examined after ultimate failure. Failure was noted to involve the hardware as well as the cadaveric bone specimens. Screws bent in one specimen representing each type of fixation. Specimens fixated with a dorsal plate showed increased deformation of the plate at the point of failure. No failure patterns were observed involving the distal screw in the proximal phalanx used for application of the wire loop testing jig.

A variety of failure patterns involved the bone of the first metatarsal and proximal phalanx. The screw heads occasionally broke the phalangeal cortex. Screw threads were also found to pull through the cancellous bone. The most common finding was channeling of the cancellous bone by both the interfragmentary screw and the crossed screws.

The channeling was more apparent with the two crossed lag screws. As the dorsal load to the phalanx increased, deeper channels were evident. The phalanx rolled dorsally with the crossed screw technique during the initial loading. The cortex would fracture and/or the phalanx would pull off of the screws, which led to gapping across the MTP joint. Although channeling and occasional breaks in the cortex occurred with the dorsal plate and single lag screw technique, the amount of gapping across the joint was less than the two crossed lag screws. It appeared that the dorsal plate helped maintain the bone contact despite channeling by the interfragmentary screw. At failure, the phalanx would roll dorsally on the conical surface of the metatarsal and the plate would bend. Complications occurred in two specimens utilizing two crossed lag screws. Upon insertion, the screws came into contact with the other requiring redrilling and possible weakening of the surrounding bone and fixation. This complication did not occur with the dorsal plate and single lag screw technique.

Discussion

This study was designed to compare quantitatively the stability of two methods of internal fixation used in first MTP joint arthrodesis achieved with convex-concave joint surface preparation. A six-hole dorsal plate with a single interfragmentary lag screw and two crossed lag screws were utilized in matched pair cadavers in our laboratory. Numerous other methods of fixation have been evaluated elsewhere and successful results have been reported with a variety of techniques (1–30).

Both fusion techniques evaluated in our laboratory maintained rigid bone contact and stability upon manual manipulation. The two crossed lag screw technique was quicker and easier to apply and used fewer materials. This may translate to shorter operating room time, lower incidence of technical error, and less cost.

The dorsal plate with a single interfragmentary screw was statistically stiffer in the first 0–1 mm of displacement under stress. This suggests that this more elaborate form of fixation may be appropriate in clinical situations where greater weightbearing demands are anticipated after surgery, such as in heavier patients, or those whose activity may be difficult to restrict. Either technique should provide satisfactory initial stability for healing when used with Coughlin's conical arthrodesis technique. The extent of postoperative protection from full propulsive weightbearing needs to be evaluated for each patient, but based on other clinical studies, casting is probably not essential (12–14, 18). There is no obvious explanation for the statistical difference in stiffness at 0–1 mm of displacement and not at 1–2 mm. Both constructs are weakened after the MTP joint is displaced by 1 mm; thus the initial construct strength is diminished. The two fixation methods may tend to lose their strength in unique patterns. Furthermore, the study is limited by a small sample, and a statistically significant difference at 1–2 mm of displacement may be apparent with a larger sample size.

Data for this study were obtained by applying a one-time load until the ultimate point of failure was achieved for each form of fixation. Therefore, this study does not address the stability of the two constructs under repetitive load conditions. Assessment of repetitive stress strength of the fixation methods used in this study requires further investigation and represents a limitation to this project.

Variation in orientation and size of the crossed screws has been described in the literature for first MTP joint arthrodesis (30). Screws with greater head diameter may reduce channeling and larger screws may improve fixation strength. In addition, changes in screw orientation may provide a more stable construct. These variables warrant further investigation to compare different constructs of crossed screw fixation for first MTP joint arthrodesis.

Conclusion

The dorsal six-hole dorsal plate with single screw fixation, and crossed screw fixation for first metatarsophalangeal joint arthrodesis may be utilized with convex-concave preparation of the joint surfaces to achieve initial stability of the fusion site. The plate and screw construct provides stiffer fixation under stress within the first 0–1 mm of motion in cadavers. This technique also demonstrated a greater ultimate point of failure, suggesting greater overall strength compared to the crossed screw technique in cadavers. In clinical situation where considerable postoperative stress on the arthrodesis is anticipated, the plate and screw fixation may be more desirable.

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