

## First Metatarsal-Phalangeal Joint Arthrodesis: A Biomechanical Assessment of Stability

Joel Politi M.D.\*; John Hayes B.S.\*\*; Glen Njus Ph.D.\*\*; Gordon L. Bennett, M.D.#; David B. Kay, M.D.#  
Akron, Ohio

### ABSTRACT

**Background:** First metatarsal phalangeal joint (MTP) arthrodesis is a commonly performed procedure for the treatment of hallux rigidus, severe and recurrent bunion deformities, rheumatoid arthritis and other less common disorders of the joint. There are different techniques of fixation of the joint to promote arthrodesis including oblique lag screw fixation, lag screw and dorsal plate fixation, crossed Kirschner wires, dorsal plate fixation alone and various types of external fixation. Ideally the fixation method should be reproducible, lead to a high rate of fusion, and have a low incidence of complications.

**Methods:** In the present study, we compared the strength of fixation of five commonly utilized techniques of first MTP joint arthrodesis. These were:

1. Surface excision with machined conical reaming and fixation with a 3.5 mm cortical interfragmentary lag screw.
2. Surface excision with machined conical reaming and fixation with crossed 0.062 Kirschner wires.
3. Surface excision with machined conical reaming and fixation with a 3.5 mm cortical lag screw and a four hole dorsal miniplate secured with 3.5 mm cortical screws.

4. Surface excision with machined conical reaming and fixation with a four hole dorsal miniplate secured with 3.5 mm cortical screws and no lag screw.

5. Planar surface excision and fixation with a single oblique 3.5 mm interfragmentary cortical lag screw.

Testing was done on an Instron materials testing device loading the first MTP joint in dorsiflexion. Liquid metal strain gauges were placed over the joint and micromotion was detected with varying loads and cycles.

**Results:** The most stable technique was the combination of machined conical reaming and an oblique interfragmentary lag screw and dorsal plate. This was greater than two times stronger than an oblique lag screw alone. Dorsal plate alone and Kirschner wire fixation were the weakest techniques.

**Conclusions:** First MTP fusion is a commonly performed procedure for the treatment of a variety of disorders of the first MTP joint. The most stable technique for obtaining fusion in this study was the combination of an oblique lag screw and a dorsal plate. This should lead to higher rates of arthrodesis.

**Key Words:** First Metatarsal Phalangeal Joint Arthrodesis; Biomechanical Testing; Stability; Hallux Rigidus; Hallux Valgus; Rheumatoid Arthritis.

### INTRODUCTION

Arthrodesis of the first metatarsophalangeal (MTP) joint is a commonly performed procedure in orthopaedics.<sup>6,7,9,13,14,15,16</sup> The first MTP joint is a frequently loaded joint which can be stressed with up to 90% of body weight during each step in gait. Rigid fixation is desired for arthrodesis of the first MTP joint to help increase the rate of bony union and maintain the desired position of fusion. There are many different types of fixation used for first MTP joint arthrodesis, including compression screws placed axially or obliquely, intramedullary Steinman pins, crossed Kirschner wires, cerclage wiring, staples, sutures, external compression clamps, external fixator, dorsal

\* 214 North Stanwood, Columbus, Ohio 43209

\*\* Department of Biomedical Engineering, University of Akron, Akron, Ohio 44309

# Crystal Clinic, Inc., 3975 Embassy Parkway, Suite 102, Akron, Ohio 44333, Associate Professor of Orthopaedic Surgery, Northeast Ohio Universities College of Medicine, Rootstown, Ohio

Corresponding Author:  
Gordon L. Bennett, M.D.  
Crystal Clinic, Inc.  
3975 Embassy Parkway, Suite 102  
Akron, Ohio 44333  
Phone: (330)-668-4040  
Fax: (330)-668-4078  
E-Mail: gbennortho@aol.com

compression plate and various combinations of the preceding techniques.<sup>5,6,7,8,11,12,14</sup> There are also several different methods of joint surface preparation described in the literature, including simple cartilage excision, planar cartilage excision using a saw, cone and socket preparation, and machined conical reaming.<sup>5,7,12</sup> Potential complications of this procedure include infection, nonunion, delayed union, malunion, metatarsal stress fractures, and local pain arising from the hardware. Reports of nonunion in the literature range from 0 to 30%.

The purpose of this study was to assess the biomechanical stability of five commonly used techniques of first metatarsal-phalangeal joint arthrodesis.

### MATERIALS AND METHODS

The five techniques of first MTP arthrodesis being studied are:

Technique 1 Surface excision with machined conical reaming and fixation with a 3.5 mm cortical interfragmentary lag screw (Fig. 1).

Technique 2 Surface excision with machined conical reaming and fixation with crossed 0.062 Kirschner wires.

Technique 3 Surface excision with machined conical reaming and fixation with a 3.5 mm cortical lag screw and a four hole dorsal miniplate secured with 3.5 mm cortical screws (Fig. 2).

Technique 4 Surface excision with machined conical reaming and fixation with a four hole dorsal miniplate secured with 3.5 mm cortical screws and no lag screw.

Technique 5 Planar surface excision and fixation with a single oblique 3.5 mm interfragmentary cortical lag screw.

The conical reaming was performed using the Biomet Truncated Conical Reamer system for first MTP joint arthrodesis (Biomet, Warsaw, Indiana) and followed the surgical technique recommended by them. A jig was developed to allow for reproducible placement of the 3.5 mm Synthes cortical lag screw in all cases. This was placed from the medial aspect of the proximal phalanx distally and directed in an oblique medial to lateral direction crossing the MTP joint and engaging the lateral cortex of the first metatarsal head, utilizing standard AO lag screw technique.

The synthetic bone models (Pacific Research Lab, Vashon Island, Washington) used in the study consisted of a standardized first metatarsal and proximal phalanx with a structure resembling that of a cortical shell and cancellous center. The modulus of elasticity for compressive strength, tensile strength, and



Fig. 1: Antero-posterior radiograph of first metatarsal-phalangeal joint arthrodesis utilizing a single 3.5 mm cortical lag screw.

shear strength is very similar to that of human cancellous bone. Detailed strength and modulus parameters are readily available. The interfragmentary screw used was a 3.5 mm Synthes cortical lag screw placed from the medial aspect of the proximal phalanx, across the MTP joint and through the lateral cortex of the 1st metatarsal, utilizing standard AO lag screw technique.

Two .062 Kirschner wires were crossed at the MTP joint for the second technique.

The third technique involved plate fixation using a four hole Vitallium miniplate (Howmedica, New Jersey), placed on the dorsal aspect of the first metatarsal and proximal phalanx and secured with dorsal to plantar directed 3.5 mm cortical screws.

The fourth technique involved fixation with an oblique 3.5 mm cortical interfragmentary lag screw followed by



**Fig. 2:** Antero-posterior radiograph of first metatarsal-phalangeal joint arthrodesis utilizing a 3.5 mm cortical lag screw and a four hole dorsal miniplate secured with 3.5 mm cortical screws.

placement of a four hole Vitallium dorsal miniplate secured with 3.5 mm cortical screws.

The fifth technique involved flat planar joint preparation and fixation with a single obliquely directed 3.5 mm cortical lag screw. The orientation of the toes was 20° of dorsiflexion, 10° of valgus, and 0° of rotation. All of these values were relative to the 1st metatarsal-phalangeal axis.

Assuming a 10% synthetic bone population variance and desiring to detect a 20% significant difference in micromotion stiffness between the groups, a power analysis concluded that eight specimens per test group would be required.

The synthetic bone models were prepared and instrumented in a uniform fashion by creating polymethylmethacrylate (PMMA) blocks to hold them in a standardized position while surface preparation cuts

were made. PMMA holding blocks were also made for the instrumentation of the toes with the different types of fixation. The use of these holding devices allowed for similar joint alignment and placement of fixation in the toes studied.

All testing was conducted using a closed loop servohydraulic material testing system (Instron 8511, Instron, Canton, MA). The system was composed of a main control panel, a servohydraulic ram, and a hydraulic fluid pump. A 900 Newton load cell (Eaton Corp., Troy, MI) was used to collect load data. Bridge amplifiers were used to amplify the output voltages of the load cell and the servohydraulic ram, as well as to provide strain gauge excitation voltages.

A data acquisition system and program (DAP, Keithly Metrabyte, Tauton, MA), installed in a personal computer, was used to convert the output signals from analog to digital and to collect data. The data acquisition program converted and organized the data, recording the data point number, strain gauge displacement, force (in kilograms), and the ram displacement.

Liquid metal strain gauges (LMSGs) were used to measure displacement across the joint space of the toe specimens. All gauges used in this study had a gauge length of 8 mm. Each LMSG (Parks Medical, Aloha, OR) was individually calibrated using the quasi-static method. Each LMSG was attached to a vernier caliper and the caliper was displaced incrementally by known distances up to approximately 2 mm. The resultant voltage at each increment was determined and a calibration curve was determined. The slope of the calibration curve was determined and used as the conversion factor between the gauge voltage and gauge displacement.

Each LMSG was securely mounted using 14 mm T-25 staples. Two LMSGs were used for each bone model. The gauges were placed across the joint line on the plantar surface of each toe model. The staple of each gauge was placed in the center of the condyles located on either side of the joint space. The gauges were oriented in a crossed fashion. The gauges crossed the joint line at specific angles. Each gauge was applied with sufficient pretension such that any opening or closing of the joint which occurred during loading was detected. Extreme care was taken to ensure identical placement of each gauge between bone models. This was accomplished by placing the staples of each gauge at the same bony landmarks.

To hold each bone model in place during loading, a clamp made of polymethylmethacrylate was developed for this study. The clamp was placed within a fixture which was attached to the ram of the Instron 8511 material testing system. The bone models were loaded only in dorsiflexion.

**Table 1:** Average Moment For Each Technique

Technique	Mean Moment
Dorsal Plate w/ Lag Screw (Technique 3)	4958.5 N-Mm
Planar Surface w/ Single Lag Screw (Technique 5)	3030.2 N-Mm
Conical Surface w/ Single Lag Screw (Technique 1)	1870.2 N-Mm
Dorsal Plate Only (Technique 4)	397.5 N-Mm
Kirschner Wires Only (Technique 2)	304.5 N-Mm

For this experiment, a triangular wave function was used to produce the desired ram displacements. The function was adjusted so that the ram displaced 7 mm, and one cycle occurred over a four second period, providing a loading rate of 3.8 mm per second. The magnitude of the haver triangle wave function was determined as the largest displacement which resulted in no fatigue loosening of the specimens. For each loading trial, data was collected at a sampling rate of 80 Hertz for 32 seconds, capturing the first eight cycles of loading.

Statistical analysis was performed to determine the effect of technique on the opening displacement across the joint space. The gauge displacement data was analyzed using SAS statistical software. A one-way analysis of variance (1-way ANOVA) was performed. If a significant difference existed, a Student-Newman Keuls (SNK) multiple range procedure was performed in order to determine where this difference existed.

## RESULTS

A total of eight synthetic bone specimen toe models were assembled for each technique. Therefore, a total of forty specimens were used for statistical analysis. The mean gauge displacement values collected during testing were resolved into a component perpendicular to the joint line. This component corresponded to an opening of the joint space. The unit directions of this component were such that a positive value corresponded to an opening of the joint space. Using the mean gauge displacements from gauges A and B, an average opening displacement was calculated. Two assumptions were made prior to resolving the data. The first assumption was that the gauges did not vary a large amount from their angle to the joint line. The second assumption was that the paired gauges remained in a plane. The second assumption allowed

for the resolved gauge displacements of the gauges to be averaged together.

In order to compare results between and within techniques, the mean gauge displacement was calculated at a specified joint opening displacement. For this study, the mean gauge displacement (the average of the eight cycles of collected data per trial) was calculated at an opening displacement of 0.9 mm which occurred during loading. The specified opening displacement was determined as 95% of the lowest peak displacement shared by all the specimens. A moment arm was used to convert forces into moments. This was the distance from the center of the condyles of the distal phalanx to the center of the joint space. This lever arm value varied slightly between specimens and their values are listed in Table 1. The moment arm length multiplied by the load determined the moment applied to the specimen.

The plate with lag screw technique (Technique 3) required the largest bending moment to open the joint space while the plate only technique (Technique 4) required the least bending moment to open the joint.

The ANOVA analysis determined that there were significant differences between the different techniques. The Student Newman Kuells (SNK) multiple range procedure determined that all of the techniques were significantly different from each other except for the plate only technique (Technique 4) and the Kirschner wire technique (Technique 2). These results are shown in Table 1. Specifically, the strongest implant was the plate and lag screw construct. It was almost three times more stable than the lag screw only construct, and in the order of 10 times more stable than either the Kirschner wire technique and the plate only technique. Of interest is the fact that the planar joint preparation was significantly stronger than the reamed joint preparation when a lag screw only technique was used.

## DISCUSSION

Previous studies have investigated the biomechanical stability of different types of fixation and surface preparation of first metatarsal phalangeal joint arthrodesis. Sykes and Hughes<sup>3</sup> used 15 pairs of cadaver toes, fixing them with cancellous screws, external fixators, and wire, with both planar joint excision and domed joint surfaces. Their results showed that a cancellous screw with planar joint excision provided the most stability. Curtis et. al.<sup>1</sup> used 10 matched pairs of cadaver toes and their results showed that conical reaming with an interfragmentary screw had the best fixation. Finally, Rongstad, et. al.<sup>2</sup> used 18 matched pairs of cadaver toes comparing a cancellous screw with a miniplate, Herbert screw, and a Steinman

pin. Their results showed the miniplate to be stronger. All three of these studies involved comparing matched pairs of cadaver toes with different types of fixation and testing them to failure by loading them in a dorsal direction. As noted earlier, the most common postoperative complication of first metatarsal phalangeal joint arthrodesis is nonunion. Rarely do these joints completely fall apart, as has been studied in these three papers.<sup>1,2,3</sup> More likely, the cause for these nonunions is a more subtle micromotion which occurs during each step in gait, as up to 90% of the body's weight is loaded onto the first metatarsal phalangeal joint.<sup>4</sup> Also, the inherent problem related to studies involving cadaver bone is the lack of standardization due to variability between specimens. This variability exists even amongst matched pairs of cadaver toes.

In our study we were able to measure the amount of micromotion which occurred across the first metatarsal phalangeal joint while simulating the forces produced during the gait cycle. We also were able to use a synthetic bone model to ensure for greater standardization and reproducibility, as all specimens which were instrumented and loaded were identical.

The plate and lag screw combination (Technique 3), which is similar to the technique which was recently recommended as the fixation of choice by Mann et al.<sup>9</sup>, provided significantly more resistance to micromotion compared to the other three methods of fixation. The oblique compression screw alone (Technique 1) provided significantly more stability across the joint than the crossed Kirschner wires (Technique 2) and the dorsal miniplate alone (Technique 4). The plate and lag screw combination (Technique 3) provides by far the most resistance to micromotion and required more than twice the force for displacement compared to the lag screw alone technique (Technique 1), which was the next strongest technique. Regarding the dorsal miniplate alone technique (Technique 4), the relatively lower resistance to micromotion can probably be explained by the positioning of the plate. Ideally the plate would be placed on the tension side of the joint, which in the dorsally loaded toe would be the plantar surface. Clinically, this cannot be readily performed because of the position of the sesamoids, and the potential problems with plantar incisions. Therefore this dorsally positioned plate is at a biomechanical disadvantage.

Regarding the types of surface preparation, the toes prepared with planar joint excision (Technique 5) were significantly more stable than those prepared with conical reaming, when fixed with oblique compression screws. The probable explanation for this difference lies in the direction of the compressive forces across the arthrodesis site. The machined conical reamers

allow for the metatarsal to slide into the proximal phalanx in an anterior to posterior direction. The oblique compression screw crosses this joint at a 45° angle, and therefore does not compress in the same direction as the sliding cone and socket allows. The planar cut joint surfaces allowed for more compression across the joint surface using the oblique compression screw.

First metatarsal-phalangeal joint arthrodeses is a commonly performed procedure in orthopaedics which can be used to correct many problems associated with the first metatarsal phalangeal joint. The ideal technique for first metatarsal phalangeal joint arthrodesis would be one which is technically simple and provides rigid fixation allowing bony union to occur. In our paper we have compared the initial stability of four different types of fixation and two types of surface preparation for a total of five techniques. We found the combination of a machined conical reaming and an oblique compression screw combined with a dorsal miniplate to be the most stable construct tested in this study.

## REFERENCES

1. **Curtis, Myerson, M., Jinnah, Cox, and Alexander, I.J.:** Arthrodesis of the First Metatarsophalangeal Joint: A Biomechanical Study of Internal Fixation Techniques. *Foot Ankle Int.* **14**:395-99, 1993.
2. **Rongstad, Miller, Vander Griend, R. and Cowin.:** A Biomechanical Comparison of Four Fixation Methods of First Metatarsophalangeal Joint Arthrodesis. *Foot Ankle Int.*, **15**:415-419, 1994.
3. **Sykes and Hughes:** A Biomechanical Study Using Cadaveric Toes to Test the Stability of Fixation Techniques Employed in Arthrodesis of the First Metatarsophalangeal Joint. *Foot Ankle Int.*, **7**:18-25, 1986.
4. **Wyss, McBride, Murphy, Cooke, and Olney, B:** Joint Reaction Forces at the First MTP Joint in a Normal Elderly Population. *Journal of Biomechanics*, **23**:977-984, 1990.
5. **Coughlin, M:** Arthrodesis of the First Metatarsophalangeal Joint with Mini-Fragment Plate Fixation. *Orthopedics*, **13**:1037-1044, 1990.
6. **Mann, R.A., and Oates, J.:** Arthrodesis of the First Metatarsophalangeal Joint. *Foot and Ankle*, **1**:159-166, 1980.
7. **Coughlin, M:** Arthrodesis of the First Metatarsophalangeal Joint. *Orthopaedic Review* **19**:177-186, 1990.
8. **Smith, Joanis, and Maxwell:** Great Toe Metatarsophalangeal Joint Arthrodesis: A User-Friendly Technique. *Foot and Ankle*, **13**:367-77, 1992.
9. **Mann, R.A.:** Disorders of the First Metatarsophalangeal Joint. *Journal of the American Academy of Orthopaedic Surgeons*, **3**:34-43, 1994.
10. **Brown, Sigal, Njus, G., Njus, N., Singerman, and Brand:** Dynamic Performance Characteristics of the Liquid Metal Strain Gage. *Journal of Biomechanics* **19**(2):165-173, 1986.
11. **Holmes, G.:** Arthrodesis of the Metatarsophalangeal Joint Using Interfragmentary Screw and Plate. *Foot and Ankle*, **13**(6):333-335, 1992.
12. **Johansson, and Barrington:** Cone Arthrodesis of the First Metatarsophalangeal Joint. *Foot and Ankle*, **4**(5):244-248, 1984.
13. **Moynihan:** Arthrodesis of the Metatarsophalangeal Joint of the Great Toe. *J. Bone and Joint Surg.*, **49B**(3):544-551, 1967.

14. **Fitzgerald**: A Review of Long Term Results of Arthrodesis of the First Metatarsophalangeal Joint. *J. Bone and Joint Surg.*, 51B(3): 488-493, 1969.
15. **Fitzgerald, and Wilkonson**: Arthrodesis of the Metatarsophalangeal

- Joint of the Great Toe. *Clin. Orthop.*, **157**:70-77, 1980.
16. **McKeever**: Arthrodesis of the First Metatarsophalangeal Joint for Hallux Valgus, Hallux Rigidus, and Metatarsus Primus Varus. *J. Bone and Joint Surg.*, **34A**:129-134, 1952.