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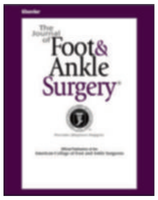
The Journal of Foot & Ankle Surgery

Contents lists available at ScienceDirect

The Journal of Foot & Ankle Surgery

journal homepage: www.jfas.org



Original Research

Progression of Healing on Serial Radiographs Following First Ray Arthrodesis in the Foot Using a Biplanar Plating Technique Without Compression

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ARTICLE INFO

Level of Evidence: 4

Keywords:
fusion
Lapidus
micromotion
rigidity
secondary bone healing
stability

ABSTRACT

A review of 195 first ray arthrodeses fixated with a twin-plate biplanar construct, without interfragmentary compression, is presented. This fixation construct was evaluated in a consecutive cohort of patients undergoing first metatarsophalangeal joint (MTP) arthrodesis or the first tarsometatarsal joint (TMT) arthrodesis. Multiple radiographs were used to assess the progression of healing at the following postoperative time frames: 4 to 9 weeks, 10 to 12 weeks, >12 weeks, and the final follow-up. In total, 85 feet underwent first MTP arthrodesis, and 110 feet underwent first TMT arthrodesis. At the final radiographic follow-up, 97.44% of all cases had shown progressive osseous gap filling at the arthrodesis site, stable position of the bone segments, and intact hardware without loosening, 98.24% of the first MTP arthrodesis group and 96.82% of the first TMT arthrodesis group. Five (5.43%) feet had the presence of lucency at the fusion interface at the final follow-up, without positional change or hardware failure. Four (1.8%) feet had a failure of the hardware, loss of position, or frank gapping at the fusion site. Lucency decreased consistently over time in this series of patients ($p < .00001$). Progressive increase in callus density at the fusion site on serial radiographs was noted to be a consistent finding for both procedures and was the primary indicator of secondary bone healing at the noncompressed, relatively stable arthrodesis site. Our results confirm that biplanar plating construct without interfragmentary compression produces high fusion rates following the first MTP or TMT arthrodesis, with early weightbearing.

Bone is a dynamic tissue, and its healing process is an essential component of the fracture treatment and reconstructive surgery. The healing potential of bone has been shown to be similar in fracture and fusion models, where a complex cascade of events takes place over weeks, months, and years as the overlapping stages of the healing progress (1). Owing to the similar healing of fusion and fracture models, the internal fixation methods for arthrodesis procedures have progressed in a manner similar to fracture fixation. Common methods include wires, compressive screws, rigid plates, and combinations of these fixation strategies. As our understanding of the ideal mechanical environment for bone healing evolves, the role of fixation to optimize healing following arthrodesis is gradually changing from a priority of rigid fixation with compression to relative stability, which can be achieved with locking plates, intramedullary constructs, and external fixation (2).

As compared with other types of tissue, bone is especially dependent on the mechanical environment to guide its repair process (3). In the context of foot arthrodesis, this mechanical environment is determined by fixation mechanics and weightbearing. Inadequate stability with excessive load can cause a failure of osseous healing (4,5). Likewise, excessive rigidity can impede the progression of osseous healing (6–8). Fixation for small bone arthrodesis most commonly employs interfragmentary compression screws, either alone or as compression screw and plate combinations. Compression techniques prioritize direct

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Financial Disclosure: None reported.

Conflict of Interest: R. Santrock and P. Dayton are consultants for Treace Medical Concepts Inc., Ponte Vedra Beach, FL.

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https://doi.org/10.1053/j.jfas.2018.09.001

osteosynthesis (primary bone healing) and by definition put the bone interface in a "rigid" state, which does not allow for micromotion and natural callus formation. Studies aiming to determine the optimal quality and quantity of interfragmentary motion to achieve bone healing have found cyclic compressive cycles that avoid the excessive shear force and torsion, increase the formation of periosteal callus, and increase the rate of osteosynthesis (9–13).

A biplanar construct for the first tarsometatarsal joint (TMT) arthrodesis was tested previously for multiplanar stability during a single static load failure and a cyclic mechanical loading, against the traditional plate and screw constructs, and, in both models, the biplanar construct was found to be superior to the compression construct (14). This construct is the basis for our current clinical observation and utilizes 2 mini titanium plates along the axis of bone at 90° to each other, without interfragmentary compression. The purpose of the present study is to assess the progression of the clinical and osseous healing when biplanar fixation without interfragmentary compression, along with early weightbearing (beginning at approximately 5 days), is employed for the first metatarsophalangeal joint (MTP) arthrodesis and the first TMT arthrodesis procedures. We hypothesize that a stable but nonrigid, noncompressed biplane locking plate construct will allow for a progressive callus healing, resulting in a stable arthrodesis.

Patients and Methods

A review of consecutive patients undergoing the first MTP or TMT arthrodesis was performed from July 2011 to January 2017 by the senior author (P.D.). Institutional review board approval was obtained. Patients were identified using the electronic CPT codes 28297 and/or 28740 review and the manual search of surgery schedules (completed by G.G.). The inclusion criteria for the present review included the primary first MTP arthrodesis or the first TMT arthrodesis in patients aged > 18 years, using 1 of the 2 specific plate sets with nearly identical mechanical characteristics (A.L.P.S. Hand Fracture System, Zimmer Biomet, Warsaw, IN, and Control 360 System, Treace Medical Concepts, Inc., Ponte Vedra, FL). For case inclusion, the plates had to be placed in a 90° biplanar construct without interfragmentary compression screws. Additional inclusion criteria were available and adequate postoperative (at least 12 weeks after the procedure) dorsoplantar, medial oblique, and lateral weightbearing radiographs. Exclusion criteria were as follows: (1) revision arthrodesis, (2) fusion performed for a failed implant, (3) clinically significant neuropathy (which was defined as a patient with a past ulceration or charcot deformity), (4) surgery owing to an acute trauma, (5) patients aged < 18 years, (6) patients not having radiographs from at least 2 time intervals, and/or (7) patients not having radiographs past 10 weeks postoperatively. The first MTP arthrodesis was performed on patients with hallux valgus deformity, decreased first MTP range of motion, painful MTP range of motion, crepitation, instability, deformity, and/or radiographic findings consistent with osteoarthritis. The first TMT arthrodesis was performed on patients with clinical and radiographic findings of hallux valgus deformity or sagittal plane deformity (instability).

More than 1 weightbearing radiograph (dorsoplantar, medial oblique, or lateral) from each interval (at 4 to 9 weeks, 10 to 12 weeks, > 12 weeks, and the final follow-up) were used to assess the radiographic healing, based on the following criteria: (1) the presence of lucency (lower radiographic attenuation than the surrounding bone) at the arthrodesis site that becomes progressively radiopaque, (2) the maintenance of the position of the arthrodesis segments, and (3) the evidence of stable hardware, without loosening or failure. The final determination of the radiographic healing was based on findings 1 to 3 described previously. The incidence of complications such as infection and wound problems and of return to shoe gear and normal activities of daily living were also obtained from a review of the medical records.

The radiographs were investigated and graded independently by 3 board-certified foot and ankle surgeons (author P.D. and 2 surgeons from the Des Moines University Foot and Ankle Clinic, who were not involved in the clinical care of the subjects in any way). Each of the investigators reviewed the digital pictures of the radiographs independently on a high-resolution computer monitor, with a research assistant (R.E. and/or J.E.) present to organize and record the raters' responses regarding the radiographic findings. Based on their "yes" and "no" answers to (1) the presence of lucency at the arthrodesis site that becomes progressively radiopaque, (2) the maintenance of the position of the arthrodesis segments, (3) the evidence of stable hardware without loosening or failure, and (4) osseous bone growth in $> 50\%$ of the arthrodesis site, the data were documented in a spreadsheet. The mean of the "yes" and "no" answers for each question at each time period was calculated separately for each physician. The χ^2 analysis was then performed, comparing each physician with one another for each question at each given time interval. The combined mean of all 3 physicians was calculated for each question at each time interval. These combined means were then compared across time intervals by using the χ^2 analysis. A p value $< .05$ (5%) was considered to indicate statistical significance. The raters' results for each of our 4 questions at each time frame were compared over the entire course of the study.

The surgical technique for the first MTP arthrodesis consisted of a dorsal linear incision medial to the extensor tendon. Direct dissection was carried down to the capsule without subcutaneous undermining, protecting the neurovascular structures in full-thickness subperiosteal skin flaps and preserving the blood supply. The capsule and periosteum were divided from the first MTP joint, exposing the articular surfaces. All cartilage and subchondral bone were resected using a rongeur and power burr, removing all cartilage and subchondral bone. Fusion site was contoured in a cup-and-cone fashion to provide complete correction of the deformity in the transverse, sagittal, and frontal planes. Temporary fixation was carried out with a smooth Kirschner wire, followed by permanent fixation with 2 small locking plates placed dorsally at 90° to each other with the help of 4 2.5 × 12 mm and 4 2.5 × 14 mm screws applied unicortically through the locking plates. In general, this would be at the 10 o'clock and 2 o'clock positions, flanking the extensor hallucis longus tendon. Temporary fixation was then removed. The capsule and skin were closed. All patients were seen for their first postoperative visit within 5 days, and all bandages were removed, without further bandaging or splinting. Patients were allowed to shower their surgical site from this point forward. Patients were instructed to ambulate in a cast boot or a postoperative shoe from the first postoperative visit at 3 to 5 days but were advised to avoid excessive or high-impact activity.

The surgical technique for the TMT arthrodesis consisted of a dorsal incision approximately 6 cm in length at the interval between the extensor hallucis and tibialis anterior tendons. Direct dissection was carried out to the level of the periosteum, which was reflected off the surfaces of the metatarsal and medial cuneiform. Following this, the sagittal saw was used to resect the articular surfaces of both the medial cuneiform and the first metatarsal base. The joint surfaces were fenestrated with a drill. Temporary fixation with Kirschner wires maintained the correction of the deformity in the transverse, sagittal, and frontal planes. Following the clinical and fluoroscopic assessment, 2 small locking plates were inserted with 4 2.5 × 12 mm and 4 2.5 × 14 mm locking screws applied unicortically through the locking plates positioned approximately 90° to each other. In general, the final positions of the plates were directly dorsal and directly medial on the TMT joint. The clinical and fluoroscopic examination showed a stable position of all hardware and the reduction of the deformity.

Results

A total of 249 cases were identified through electronic CPT code review and the manual search of surgery schedules. A clinical and radiographic review of 195 feet was carried out after the application of the inclusion and exclusion criteria. Sixteen cases were excluded because their medical records were not available or not complete, 20 cases were excluded for the lack of radiographs beyond the 11-week point, 4 were a revision of other procedures not using biplanar plating, 3 were patients with acute trauma, 3 had a graft placed, 4 had biplanar plating but not the plate systems specified, and 4 had clinically significant neuropathy for a total number excluded of 54 (22%) of 249 cases. The mean patient age for the MTP arthrodesis and the TMT arthrodesis was 59 (range 22 to 80) years and 34 (range 12 to 69) years, respectively. The median and mean times of the last follow-up of the MTP study group and the TMT study group were 30 weeks and 38 (range 12 to 240) weeks, respectively, and the median and mean times for the radiographic evaluation of the MTP study group and the TMT study group were 32 weeks and 45 (range 12 to 200) weeks, respectively. A total of 29 patients were active smokers, and 9 patients had well-controlled diabetes.

The radiographic assessments of the 3 surgeons can be seen in Tables 1–3 (all statistical analysis was performed by R.E.). After sequential data analysis, substantial inconsistencies were found in the application of the reading guidelines by the third investigator. We have included the third investigator's data in Table 4 but omitted these data points in the final data analysis (Table 5) for the following reason: there were inconsistencies in the application of the reading guidelines, which resulted in values statistically different ($p < .00001$ and $p < .00001$) from the values by the other 2 raters, which were statistically consistent ($p = 0.521$). A review of every instance that showed disagreement was undertaken, and we confirmed that the ratings were not consistent with the radiographic findings. Inclusive of this investigator's ratings, 92.7% of feet would be rated as healed. The presence of lucency of the

Table 1
Percentage of patients who fit into each of the categories from the first surgeon (P.D.) (N = 195)

Weeks	Questions	MTP Arthrodesis		TMT Arthrodesis		Total*	
		Yes	No	Yes	No	Yes	No
6	Presence of lucency?	58.02	41.98	53.85	46.15	55.68	44.32
	Hardware failure or loosening?	0	100	0	100	0	100
12	Presence of lucency?	18.57	81.43	32.65	67.35	26.79	73.21
	Stable position?	100	0	98.98	1.02	99.40	0.60
	Hardware failure or loosening?	0	100	0	100	0	100
	Increase in radiodensity and trabecular pattern?	95.71	4.29	96.94	3.06	96.43	3.57
26	Presence of lucency?	7.69	92.31	11.11	88.89	9.49	90.51
	Stable position?	100	0	98.61	1.39	99.27	0.73
	Hardware failure or loosening?	1.54	98.46	0	100	0.73	99.27
	Increase in radiodensity and trabecular pattern?	98.46	1.54	97.22	2.78	97.81	2.19
52	Presence of lucency?	5.13	94.87	3.70	96.30	4.35	95.65
	Stable position?	100	0	98.15	1.85	98.91	1.09
	Hardware failure or loosening?	0	100	1.85	98.15	1.09	98.91
	Increase in radiodensity and trabecular pattern?	97.44	2.56	98.15	1.85	97.83	2.17
Final follow-up	Is there osseous bone growth in > 50% of the arthrodesis site?	96.47	3.53	97.27	2.73	96.92	3.08

Abbreviations: MTP, metatarsophalangeal joint; TMT, tarsometatarsal joint.

[*] Total refers to the results of the MTP and TMT arthrodeses.

Table 2
Percentage of patients who fit into each of the categories from the second surgeon (E.N.) (N = 195)

Weeks	Questions	MTP Arthrodesis		TMT Arthrodesis		Total*	
		Yes	No	Yes	No	Yes	No
6	Presence of lucency?	67.90	32.10	47.12	52.88	56.22	43.78
	Hardware failure or loosening?	1.23	98.77	1.92	98.08	1.62	98.38
12	Presence of lucency?	41.43	58.57	28.57	71.43	33.93	66.07
	Stable position?	100	0	98.98	1.02	99.40	0.60
	Hardware failure?	2.86	97.14	1.02	98.98	1.79	98.21
	Increase in radiodensity and trabecular pattern?	98.57	1.43	98.98	1.02	98.81	1.19
26	Presence of lucency?	15.38	84.62	9.72	90.28	12.41	87.59
	Stable position?	100	0	98.61	1.39	99.27	0.73
	Hardware failure or loosening?	3.08	96.92	2.78	97.22	2.92	97.08
	Increase in radiodensity and trabecular pattern?	96.92	3.08	98.61	1.39	97.81	2.19
52	Presence of lucency?	10.26	89.74	3.70	96.30	6.52	93.48
	Stable position?	100	0	98.15	1.85	98.91	1.09
	Hardware failure or loosening?	2.56	97.44	1.85	98.15	2.17	97.83
	Increase in radiodensity and trabecular pattern?	97.44	2.56	98.15	1.85	97.83	2.17
Final follow-up	Is there osseous bone growth in > 50% of the arthrodesis site?	100	0	96.36	3.64	97.95	2.05

Abbreviations: MTP, metatarsophalangeal joint; TMT, tarsometatarsal joint.

[*] Total refers to the results of the MTP and TMT arthrodeses.

Table 3
Percentage of patients who fit into each of the categories from the third surgeon (J.M.) (N = 195)

Weeks	Questions	MTP Arthrodesis		TMT Arthrodesis		Total*	
		Yes	No	Yes	No	Yes	No
6	Presence of lucency?	93.83	6.17	96.15	3.85	95.14	4.86
	Hardware failure or loosening?	2.47	97.53	0.96	99.04	1.62	98.38
12	Presence of lucency?	82.86	17.14	88.78	11.22	86.31	13.69
	Stable position?	100	0	100	0	100	0
	Hardware failure or loosening?	1.43	98.57	2.04	97.96	1.79	98.21
	Increase in radiodensity and trabecular pattern?	100	0	100	0	100	0
26	Presence of lucency?	66.15	33.85	54.17	45.83	59.85	40.15
	Stable position?	100	0	100	0	100	0
	Hardware failure or loosening?	0	100	1.39	98.61	0.73	99.27
	Increase in radiodensity and trabecular pattern?	100	0	98.61	1.39	99.27	0.73
52	Presence of lucency?	46.15	53.85	27.78	72.22	34.78	65.22
	Stable position?	100	0	100	0	100	0
	Hardware failure or loosening?	0	100	0	100	0	100
	Increase in radiodensity and trabecular pattern?	97.44	2.56	100	0	98.91	1.09
Final follow-up	Is there osseous bone growth in > 50% of the arthrodesis site?	84.71	15.29	81.82	18.18	83.08	16.92

Abbreviations: MTP, metatarsophalangeal joint; TMT, tarsometatarsal joint.

[*] Total refers to the results of the MTP and TMT arthrodeses.

Table 4
Percentage of patients who fit into each of the categories after readings from all surgeons were averaged by the mean and tallied (N = 195)

Weeks	Questions	MTP Arthrodesis		TMT Arthrodesis		Total[*]	
		Yes	No	Yes	No	Yes	No
6	Presence of lucency?	73.25	26.75	65.71	34.29	69.01	30.99
	Hardware failure or loosening?	1.23	98.77	0.96	99.04	1.08	98.92
12	Presence of lucency?	47.62	52.38	50	50	49.01	50.99
	Stable position?	100	0	99.32	0.68	99.60	0.40
	Hardware failure or loosening?	1.43	98.57	1.02	98.98	1.19	98.81
	Increase in radiodensity and trabecular pattern?	98.10	1.90	98.64	1.36	98.41	1.59
26	Presence of lucency?	29.74	70.26	25	75	27.25	72.75
	Stable position?	100	0	99.07	0.93	99.51	0.49
	Hardware failure or loosening?	1.54	98.46	1.39	98.61	1.46	98.54
	Increase in radiodensity and trabecular pattern?	98.46	1.54	98.15	1.85	98.30	1.70
52	Presence of lucency?	20.51	79.49	11.32	88.68	15.22	84.78
	Stable position of the arthrodesis?	100	0	98.74	1.26	99.28	0.72
	Hardware failure or loosening?	0.85	99.15	1.26	98.74	1.09	98.91
	Increase in radiodensity and trabecular pattern?	97.44	2.56	98.74	1.26	98.19	1.811
Final follow-up	Is there osseous bone growth in > 50% of the arthrodesis site?	93.73	6.27	91.82	8.18	92.65	7.35

Abbreviations: MTP, metatarsophalangeal joint; TMT, tarsometatarsal joint.
[*] Total refers to the results of the MTP and TMT arthrodeses.

Table 5
Percentage of patients who fit into each of the categories after ratings from the first and second surgeons (P.D., E.N.) were averaged by the mean and tallied (N = 195)

Weeks	Questions	MTP Arthrodesis		TMT Arthrodesis		Total[*]	
		Yes	No	Yes	No	Yes	No
6	Presence of lucency?	62.96	37.04	50.48	49.52	55.95	44.05
	Hardware failure or loosening?	0.62	99.38	0.96	99.04	0.81	99.19
12	Presence of lucency?	30	70	30.61	69.39	30.36	69.64
	Stable position?	100	0	98.98	1.02	99.40	0.60
	Hardware failure or loosening?	1.43	98.57	0.51	99.49	0.89	99.11
	Increase in radiodensity and trabecular pattern?	97.14	2.86	97.96	2.04	97.62	2.38
26	Presence of lucency?	11.54	88.46	10.42	89.58	10.95	89.05
	Stable position?	100	0	98.61	1.39	99.27	0.73
	Hardware failure or loosening?	2.308	97.69	1.39	98.61	1.82	98.18
	Increase in radiodensity and trabecular pattern?	97.69	2.31	97.92	2.08	97.81	2.19
52	Presence of lucency?	7.69	92.31	3.77	96.23	5.43	94.56
	Stable position?	100	0	98.11	1.89	98.91	1.09
	Hardware failure or loosening?	1.28	98.72	1.89	98.11	1.63	98.37
	Increase in radiodensity and trabecular pattern?	97.44	2.56	98.11	1.89	97.83	2.17
Final follow-up	Is there osseous bone growth in > 50% of the arthrodesis site?	98.24	1.76	96.82	3.18	97.44	2.56

[*] Total refers to the results of the MTP and TMT arthrodeses.

fusion site was decreased by a statistically significant amount ($p < .00001$) at $\alpha = 0.05$ over the course of the study if the third investigator's results had been included in the final data analysis.

At the final radiographic follow-up, 97.4% of all cases had shown progressive gap filling, stable position of the bone segments, intact hardware without loosening, and osseous bone filling at the arthrodesis site. This included 98.2% of the first MTP arthrodesis cases and 96.8% of the first TMT arthrodesis group. Five (5.4%) feet had the presence of a faint lucency at the fusion interface at the final follow-up, without positional change or hardware failure. Four (1.8%) feet had a failure of the hardware, loss of position, or frank gapping at the fusion site at 26 weeks. Lucency decreased consistently over time in this series of patients ($p < .00001$). Lucency was significantly different (at $\alpha < 0.05$) between weeks 6 versus 12, 12 versus 26, and 26 versus 52, all showing improvement or gap filling at the fusion site for both the MTP arthrodesis patients and the TMT arthrodesis patients. Over the course of the study, the total failure percentage stayed between 0.8% and 1.8%, the stable percentage stayed between 98.9% and 99.4% (Tables 6 and 7), and the percentage that had a progressive increase in the radiodensity and trabecular patterns ranged from 97.6% and 97.8%.

Table 6
Results of radiographic assessment reported in ranges of percentage over time for the specific assessments listed, reported separately and combined for MTP and TMT arthrodeses (N = 195)

Assessment	MTP Arthrodesis (%)	TMT Arthrodesis (%)	Total (%)[*]
Maintenance of stable position	100	98.15 to 98.98	98.91 to 99.40
Hardware failure or loosening	0.62 to 2.31	0.51 to 1.85	0.81 to 1.82
Increasing radiodensity/ trabecular pattern	97.14 to 97.69	97.92 to 98.15	97.62 to 97.83

[*] Total refers to the results of the MTP and TMT arthrodeses.

Table 7
Results of χ^2 test for change in lucency at specified times during the postoperative period (N = 195)

Comparison by weeks	MTP Arthrodesis *p* Value	TMT Arthrodesis *p* Value	Total *p* Value[*]
6 versus 12	< .00001[†]	.000049[*]	< .00001[†]
12 versus 26	.000204[†]	< .00001[*]	< .00001[†]
26 versus 52	.404	.053	.045[†]

[*] Total refers to the results of the MTP and TMT arthrodeses.
[†] Significant result ($\alpha < 0.05$).

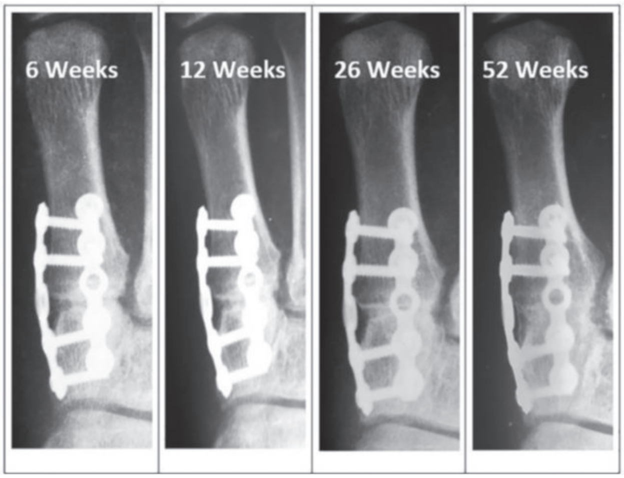

Fig. 1. First tarsometatarsal joint arthrodesis healing progression. Note the progressive filling in of the arthrodesis gap over time.

Postoperative complications necessitating reoperation included 5 hardware removals (1 MTP arthrodesis and 4 TMT arthrodesis) for prominent or painful hardware and 1 reoperation for complete displacement of hardware from bone, which resolved uneventfully with the reoperation and repair with biplanar plating, for a reoperative intervention rate of 3.1%. There were 16 unique cases of superficial wound complications, consisting of 12 superficial infections and 7 wound dehiscence or suture responses, for a superficial skin complication rate of 8.2%. One incision and drainage with culture was performed in the office, with complete resolution of symptoms and healing without further surgery. All superficial infections demonstrated complete resolution with oral antibiotics, and no deep tissue infections requiring operative intervention or intravenous antibiotics occurred. All superficial skin complications resolved uneventfully with appropriate office-based therapy.

Discussion

This review demonstrates that a biplanar plating construct without a compression screw can provide the appropriate mechanical environment to allow bone healing following the first MTP or TMT arthrodesis, when the patients are allowed protected early weightbearing by using a fracture boot. The rates of union were similar to the reports on union following compression fixation for these procedures (15–18). As our knowledge and understanding of optimal biologic bone healing has expanded, the fixation constructs used for fracture and arthrodesis healing have evolved. Traditional rigid fixation constructs rely on a static compressive load at the bone-to-bone interface to produce friction and achieve absolute stability. This type of fixation construct utilizes compression screws to develop interfragmentary friction, which provides resistance to the displacement of the bone segments. However, this philosophy of internal fixation allows for only direct or primary bone healing, without callus formation. The traditional goal of producing primary healing over secondary healing with callus formation has recently been called into question, because callus healing (natural healing) achieves biologic stability quicker than the primary healing, especially with mechanical loading of the site, which is seen with early weightbearing, as will be discussed in the next paragraph.

A mechanical environment of relative stability, as opposed to rigidity, allows controlled micromotion at the bone-to-bone interface and leads to secondary bone healing by callus formation. Secondary healing has been shown to increase the cross-sectional stability of the healing site and decrease time to healing (2,19). In 2004, Hente et al (12) used tibial osteotomies in sheep to demonstrate that micromotion in the form of cyclic compressive displacement allowed for significantly more callus formation and a stronger healing construct. In 2017, a standardized large animal model was used to compare the use of a compression plate and an active plate (which allowed for controlled micromotion); it was found that, at 9 weeks, the active plate cohort had a 6 times larger callus area and had recovered 42% more of their strength than their compression plate counterparts (20). The use of compression screws to create static compression at a healing site does not permit cyclic compressive displacement to allow for secondary bone healing. Further, osteotomies have been shown to heal with 68% more callus formation when using a titanium plate as compared with stainless steel plates, which exhibit twice as much stiffness (21).

Multiplanar stability at the bone-to-bone interface can be obtained without static compression or rigidity by using biplanar plating. Studies of biplanar plating in humerus fractures have determined that parallel locking plates oriented 90° to 180° from each other are able to achieve multiplane stability while avoiding the excessive rigidity seen with compression fixation (22–24). In addition to the mechanical advantages of biplanar plating, the elimination of the interfragmentary compression screw allows for the maximal surface area contact at the fusion site, increasing the potential healing surface area. This property of the fixation construct may be contributing to the high fusion rates demonstrated in this study.

Many studies on bone healing evaluate the surgical site at 1 specific time point during recovery. This common practice may not fully define the actual healing of the site, especially when tightly compressed surfaces are evaluated using standard radiographs. In the case of arthrodesis procedures, the most consistently used measure of union is the continuity of the trabecular pattern across the arthrodesis segments, observed on radiograph, which is subjective and not always accurate. Recent computed tomographic (CT) studies have called into question the accuracy of the radiographic evaluation of osseous union, showing that the radiographic assessment of the extent of healing in both forefoot and hindfoot arthrodeses shows poor agreement when compared with the CT findings (25). Although radiographs are unable to evaluate the extent of healing that has taken place at an individual time point, progressive healing with increasing radiodense bridging and decreasing radiolucency is observable with serial radiographs. Progressive callus formation was observed in the present study, indicated by the fact that the lucency was seen at the fusion interface in the early points of recovery that are progressively obliterated over time. The presence of lucency during the healing process most likely indicated that immature callus was present at the fusion site. A strong indication of healing was a progressive decrease in lucency through time, indicative of the maturation of callus within the fusion site. Lucency was present in 56.0% of all feet at 6 weeks, 30.4% at 12 weeks, 11% at 26 weeks, and 5.4% at the final follow-up; these results were statistically significant at a $p < .00001$, indicating that osseous bridging and gap filling are occurring. Gap filling was present in >97.1% of all radiographs at the 12, 26, and 52-week intervals, indicating that the mechanical environment produced by the biplanar plating construct does enable callus formation throughout the course of healing. The low rate of hardware failure leads to the conclusion that this biplane plating construct possesses the strength to uphold the mechanical demands of early weightbearing during recovery.

With compression fixation, a gap at a compressed surface is not seen; therefore, it is impossible to assess the degree of bone healing with surety at that point in time. In other words, a lack of gap does not assure us that primary healing is complete or inform of the rate at which it is progressing. The main indicator of healing with compression fixation is the absence of the separation of the surfaces over time, but as noted previously, this infers that the bone repair is occurring but cannot assure the stage to which healing has reached. There is no direct positive radiographic finding of the primary osseous healing. The biplanar

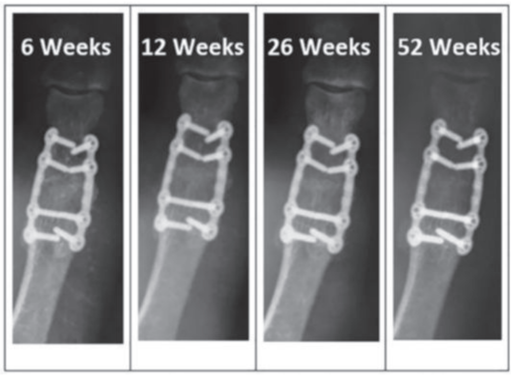

Fig. 2. First metatarsalphalangeal joint arthrodesis healing progression. Note the progressive filling in of the arthrodesis gap over time

plating construct described in this study allows for an excellent visualization of the fusion site throughout the healing process, so that the direct observation of healing is progressing. Conversely, anatomic plating techniques with wide or large plates limit the ability to evaluate healing by obscuring a large portion of the fusion site, especially on anteroposterior radiographs, when the plates are placed dorsally, as is most common.

In this series, healing was evaluated on radiographs by considering 3 factors: the evidence of progressive gap filling, the lack of hardware loosening, and the maintenance of bone segment position. The final assessment of stable union was stable trabecular bone at the fusion site at the final follow up (with a final mean healing rate of 97.4%). Clinical indicators from the patients' medical record included resolution of pain at the surgical site and pain-free return to function. Multiple radiographs were evaluated for healing progression in series rather than individually, because these progressive changes assure us that healing is occurring over time. Owing to osteoclastic resorption that occurs during the trajectory of bone healing, a lucency at the fusion interface is commonly visualized when using a relatively stable noncompressed construct, and filling of the gap indicates secondary healing progress. This phenomenon, which is typically apparent on radiographs around weeks 6 to 12, can be mistaken for a delayed healing or the regression of healing when viewed independently. When using compression or friction-based fixation, a visible gap at the early stages indicates fixation failure and at the late stages indicates failure of the fusion or healing of fracture. On the other hand, with noncompressed surfaces and callus healing, a lucency is expected, and progressive filling confirms healing. Signs of motion between the osseous segments, evidenced by hardware motion, failure of hardware, loss of position of the segments, and increasing lucency or gap at the fusion site, indicate failure or delay of union. Conversely, lack of motion and stable position on progressive radiographs are suggestive of union, particularly in our series, where immediate or early weightbearing was instituted. These results showed a consistent radiographic stability, without hardware failure, screw loosening, or positional change, with 99.4% being stable at 12 weeks, 99.3% being stable at 26 weeks, and 98.9% being stable at 52 weeks. The lack of clinical motion at the fusion site and the lack of pain and edema are also suggestive of union, because motion at the arthrodesis site would produce these symptoms. Patients were able to walk comfortably in a controlled ankle motion boot during recovery.

The absolute amount of bridging required to definitively constitute a union is not yet established, but it has been suggested that 50% of bridging is a reasonable definition. A study by Coughlin et al (25) comparing CT with plain film radiograph assessing the amount of healing in hindfoot arthrodesis showed that the ongoing osseous bridging across the surface area of the joint continues until at least the 12-month mark. Assessing an arthrodesis as healed or fused at a finite point, especially early in the process of healing, may be the wrong way to approach the issue at hand, particularly with plain radiographic examination. Owing to this fact, we used a comparison of multiple time points to determine the healing progress. An arthrodesis could more accurately be characterized as clinically and radiographically stable with progressive healing changes rather than as healed or fused, particularly in the first year after the surgery. Because of the extended timing for complete osseous bridging, it is a necessity to have a construct that maintains stability over time and with weightbearing. The biplane construct described maintained stability with weightbearing throughout the course of gap filling, with a failure rate of 0.8% at 6 weeks, 0.9% at 12 weeks, 1.8% at 26 weeks, and 1.6% at 52 weeks.

As with all studies, our experimental design has limitations that may affect the conclusions brought forth. Readers should consider all potential bias and study limitations when they critically assess these findings. Radiographs were utilized in this study, which may not demonstrate the degree of osseous bridging accurately in all instances. In the past, the CT images have been shown to be superior to radiographs for the demonstration of radiographic bridging (25). However, in clinical practice, radiographs are a more realistic imaging modality owing to cost and timing and are well suited for demonstrating progressive healing when the fixation construct allows visualization of the fusion site and can demonstrate progressive healing over time. The position at which the x-ray images were taken can affect the radiograph; therefore, in order to minimize this effect, we provided 2 radiograph views for the readers' evaluation at each time period. Subjectivity exists in the evaluation of radiographic findings, and there are variations between the opinions of providers. We attempted to control for the subjectivity by having multiple experienced surgeons evaluate the radiographs independently. We could also be criticized for omitting the results of 1 of the surgeons from the final data analysis, based on what we confirmed to be a deviation from the study protocol. We critically evaluated the inconsistent findings and feel confident in our analysis. Furthermore, we have included these data points for the third investigator, so that the readers can draw their own conclusions. Radiograph quality is important in clinical decision making. All of the x-ray images were not digital, which is a limitation in this study.

In conclusion, our results demonstrate the ability of a biplanar plating construct to provide reliable stability sufficient to withstand early weightbearing and return to function, resulting in progressive bone healing and ultimately stable fusion for the first MTP arthrodesis and first TMT arthrodesis procedures. Lucency at the arthrodesis site progressively decreased during the postoperative period for both the MTP and TMT arthrodeses, indicating progression of callus healing. Multiplane stability at the bone-to-bone interface can be obtained without static compression or rigidity by using a biplanar plating construct for the first MTP arthrodesis and first TMT arthrodesis procedures. Future research is needed to determine whether bone healing is stronger when biplanar plating is performed with or without a compression screw.

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TSP D64905

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