The Journal of Foot & Ankle Surgery 59 (2020) 291–297

Contents lists available at ScienceDirect

The Journal of Foot & Ankle Surgery

journal homepage: www.jfas.org

Comparison of Radiographic Measurements Before and After Triplane Tarsometatarsal Arthrodesis for Hallux Valgus

Paul Dayton, DPM, MS, FACFAS[1], Stefany Carvalho, BS[2], Rachel Egdorf, DPM[3], Mindi Dayton, DPM, MHA, FACFAS[1]

[1] Surgeon, Foot & Ankle Center of Iowa/Midwest Bunion Center, Ankeny, IA
[2] Student, Des Moines University College of Podiatric Medicine and Surgery, Des Moines, IA
[3] Resident, AMITA Saint Joseph Hospital Chicago, Chicago, IL

ARTICLE INFO

Level of Clinical Evidence: 4

Keywords:
bunion surgery
deformity apex
frontal plane
recurrence
rotation

ABSTRACT

We present a comparison of preoperative and final postoperative first ray measurements in 109 feet after triplane tarsometatarsal arthrodesis at a mean follow-up time of 17.4 months. Preoperative and final postoperative first ray variables including intermetatarsal angle (IMA), hallux valgus angle (HVA), tibial sesamoid position (TSP), distal metatarsal articular angle (DMAA), Seiberg index, metatarsal rotation angle (MRA), sesamoid subluxation, osseous union, and hardware failure were evaluated. Measurements were made by consistently using the mid-diaphyseal line of the bone segments for both preoperative and postoperative assessments. The mean preoperative HVA, IMA, and TSP were 22.9°, 13.3°, and 4.6. The mean differences (95% confidence interval) in preoperative and postoperative values were −14.9° (−16.3° to −13.4°) for HVA, −7.7° (−8.2° to −7.2°) for IMA, and −2.6 (−2.8 to −2.3) for TSP. Among bunions with MRA measurements, the mean difference was −12.3° (−14.5° to −10.0°). The preoperative to postoperative DMAA decreased by a mean of −14.2° (−15.9° to −12.6°). The results of this study suggest that triplane tarsometatarsal arthrodesis produces appropriate correction of hallux valgus radiographic parameters.

Algorithms for selecting a hallux abducto valgus (HAV) procedure rely primarily on 2-dimensional (2D) measurements such as intermetatarsal angle (IMA), hallux valgus angle (HVA), tibial sesamoid position (TSP), and distal metatarsal articular angle (DMAA) measurements (and therefore are 2D). Based on these measurements, it is not surprising that HAV correction is most commonly surgically addressed as a biplanar deformity, with angular and sliding osteotomies and capsular balancing procedures attempting only to correct transverse and sagittal plane angular deformities. This biplane thought process has resulted in recurrence rates as high as 73%, along with other complications, which may be be due to failure to correct all 3 planes of the deformity (1).

Surgeons have complicated the topic of HAV and introduced bias in study results by using dual measurements to assess pre- and postoperative IMA (2). The anatomic IMA (aIMA) is the bisection of the mid-diaphyseal osseous segments of metatarsals 1 and 2. The mechanical IMA is the line connecting the midpoint of the tarsometatarsal joint (TMT) and metatarsophalangeal joint (MTPJ) articular surfaces. When using the aIMA before surgery and the mechanical IMA after surgery, which is commonly taught, observation bias occurs. This practice overestimates correction of all of the angular measurements defining HAV deformity (3). Because osteotomy creates a deformity in a normally straight metatarsal, these angular measurements are not valid postoperatively. We believe this practice prevents accurate understanding of the outcomes of the dozens of osteotomy procedures described for bunion correction and prevents the development of best-practice protocols.

In contrast to the more traditional 2D osteotomy approach for bunion correction, the foot and ankle community has seen a renewed interest in the study of the 3D anatomy of the HAV deformity and the application of triplane corrective procedures. Relatively few clinical studies exist reporting the results of the 3D concept for correction. This study is a retrospective analysis of radiographs from a group of patients with HAV who underwent triplane TMT correction. Objectives of this study include comparison of preoperative and final postoperative first ray measurements including IMA, HVA, TSP, DMAA, Seiberg index (SI), lateral round sign (LRS), metatarsal rotation angle (MRA), sesamoid subluxation, osseous union, and hardware failure using a uniform anatomic measurement technique based on the mid-diaphyseal line of the bone segments for both preoperative and postoperative assessments.

Financial Disclosure: None reported.

Conflict of Interest: P.D. has been performing triplane TMT arthrodesis exclusively for nondegenerative bunions since 2009. He has worked as a consultant and design team surgeon with Treace Medical Concepts, Inc., since 2014. The other authors declare no conflicts of interest.

Address correspondence to: Paul Dayton, DPM, Foot & Ankle Center of Iowa/Midwest Bunion Center, 3720 N. Ankeny Blvd, Suite 103 Ankeny IA 50023.

E-mail address: daytonp@icloud.com (P. Dayton).

https://doi.org/10.1053/j.jfas.2019.08.020

We hypothesized that deformity correction measured with aIMA both preoperatively and postoperatively would be consistent across a wide range of patient characteristics and deformities and that the rate of recurrence would be low.

Patients and Methods

Consecutive radiographic records of patients who underwent triplane TMT arthrodesis for symptomatic hallux valgus from January 6, 2014, to January 7, 2017, were identified through review of surgical records of the lead author (P.D.). The Des Moines University Institutional Review Board approved the records review. Inclusion criteria considered in selecting the records for final review included closed physeal plates at the time of procedure; preoperative IMA 10.0° to 25.0°; preoperative HVA 15.0° to 40.0°; acceptable surgical candidate, including the use of general anesthesia; and pre- and postoperative radiographs available. The following criteria resulted in the exclusion of records: previous surgery for hallux valgus on operative side; moderate or severe osteoarthritis of the MTPJ based on radiographic imaging and clinical examination (limited and painful range of motion, crepitus); or incomplete radiographic records.

Standard weightbearing anterior-posterior (AP), lateral, and axial radiographs taken during treatment were studied. HVA, IMA, MRA, LRS, SI, sesamoid subluxation, and TSP were measured or assessed using the anatomic axis of the first metatarsal preoperatively and the same anatomic axis reference at final follow-up. Two investigators (S.C., P.D.) performed the measurements. Measurement technique was consistent with recommendations made by Gerbert (4). Secondary end points were the presence of recurrence and rate of successful union. We used a strict definition for recurrence, with values being within the normal range most commonly cited for HAV (HVA ≤15°, IMA ≤10°, and TSP ≤3).

IMA is defined as the angle formed by longitudinal bisection of the first metatarsal and second metatarsal anatomic axes on AP projection; normal IMA is ≤10.0°. HVA is the angle formed by bisection of the longitudinal anatomic axis of the proximal phalanx and first metatarsal on AP projection; normal HVA is ≤15.0°. TSP is the relationship of tibial sesamoid to the bisection of the shaft of the first metatarsal on AP projection; normal TSP is ≤3. DMAA is the angle formed by a line perpendicular to longitudinal bisection of the first metatarsal and a line formed by marking points of medial and lateral aspects of first metatarsal head cartilage (perceived distal articular cap) on AP projection; normal DMAA is <8.0°. MRA is assessed on semiweightbearing sesamoid axial view relative to the lesser metatarsals. LRS (lateral rounding of the first metatarsal head) as described by Okuda et al (5) was assessed on AP radiograph. Sesamoid subluxation is accessed on the plantar-axial projection in which sesamoids are observed for any lateral subluxation out of their normal position in their respective grooves, the crista is evaluated, and erosion of this structure by lateral subluxation of the tibial sesamoid, if present, is noted. SI was assessed on the lateral radiograph as the relationship of the dorsal cortical line of the first metatarsal relative to the second metatarsal and reported as dorsal, neutral, or plantar. Union was defined as progressive increase in radiodensity at the arthrodesis interface, absence of hardware loosening or failure, and maintenance of position based on the scoring evaluation found in Karthas et al (6). Clear evidence of loosening with osteopenic halo around screws or >1 screw or either of the biplane plates breaking defined hardware failure. Descriptive statistics were used to evaluate baseline characteristics and outcome measures. Means, standard deviations, and 95% confidence intervals are reported for continuous variables, and percentages are reported for categorical variables.

Surgical Procedure

All patients were evaluated clinically and radiographically and determined to be satisfactory candidates for the surgical procedure from a medical standpoint. Nonsurgical care and preoperative consent were based on accepted standards of the American College of Foot & Ankle Surgeons treatment guidelines (7). Two similar techniques were represented, including free hand correction and the Lapiplasty instrumented system (Treace Medical Concepts) (7). Both techniques specifically corrected all 3 planes of the deformity, and both used biplane locking plate fixation with the 2 plates placed with the screw angles at or close to 90° to each other. The mechanical characteristics of the 2 plating systems were similar (Control 360 from Treace Medical Concepts and Alps Hand Fixation System from Biomet). Procedures were performed with general anesthesia or local anesthesia with sedation based on medical appropriateness and patient preference. All procedures were performed in the supine position with standard extremity preparation, chlorhexidine/alcohol preparation, and a single dose of prophylactic antibiotic given within 30 minutes of initial incision. Thigh tourniquet hemostasis was used. The first step involved a lateral sesamoid ligament release through a small interspace incision only if there was sesamoid subluxation or clinically significant lateral ankylosis. No further soft tissue release was carried out (no release or dissection of the dorsal capsule, no tendon releases or transfers, and no capsular plication medially). In the majority of the cases, medial metatarsal head resection was not performed.

The incision for the TMT fusion was placed dorsal directly over the joint and just medial and adjacent to the long extensor of the hallux. Dissection of the subcutaneous plane was avoided to preserve the perforating blood supply. The majority of the tissue separation was subcapsular and subperiosteal. The TMT joint was released to allow triplane repositioning. The ability to entirely correct the deformity before bone resection was confirmed on fluoroscopy. Next, the joint surfaces were resected, including cartilage and all subchondral bone. Cuts were oriented to correct the transverse and sagittal components as needed, with the first metatarsal cut perpendicular to the long axis of the metatarsal. The cuneiform cut was made perpendicular to the long axis of the second metatarsal. The distal medial portion of the cuneiform was left intact, allowing reduction of the intermetatarsal without sacrificing significant length of the first ray. The rotational deformity of the metatarsal was addressed by axial rotation of the bone in a varus, or invertion, direction (supination) until congruous alignment of the first MTPJ and sesamoids was observed clinically and on fluoroscopic exam. The segments were next temporarily stabilized with wires. Final fixation consisted of 2 small flexible locking plates placed dorsal and medial using 1 of the 2 plating systems noted above. The fusion site was positioned with the dorsal and medial cortices flush in all cases. No sliding offset was performed in any plane—that is, all correction in the sagittal and transverse planes was angular. Closure was completed with absorbable suture for the deep layer (1 layer only, since there was no subcutaneous layer undermining) and combination of intradermal absorbable suture and nonabsorbable skin closure as determined appropriate for each patient.

Postoperative regimens were consistent across the cohort, with all patients being seen for their first postoperative evaluation within the first week. At that visit, all bandages were removed, and the patient was given a light compression sock, fitted with a tall fracture boot, and allowed to begin to bear weight as tolerated. Showering of the operative extremity was allowed at this time, and no bandages, skin medications, or splinting of the hallux was recommended. Intermittent, low-impact activities were specified, and the patient was instructed to remove the boot several times per day to begin active and passive range of motion of the foot and ankle. The boot was removed for sleeping.

Results

There were 108 subjects and 109 bunions that met criteria in this study (1 subject had both feet corrected). The majority of subjects were female (95.4%), and the mean age was 33.9 years (standard deviation 14.1). The mean follow-up time was 17.4 months (9.6). All bunions (100%) were healed after TMT triplane correction, and 1 foot (0.9%) experienced deformity recurrence. There were no cases of hardware failure reported (Table 1).

Eighty-five percent of bunions (n = 93) had a positive LRS before surgery, and postoperatively there were no bunions (0%) with a positive LRS. The SI was similar before and after surgery, with 82.7% and 86.0% of bunions being neutral, respectively; 9.6% and 10.5% of bunions were plantarflexed pre- and postoperatively; and 7.7% and 3.5% of bunions were dorsiflexed pre- and postoperatively. Rates of sesamoid subluxation decreased postoperatively, with 31.6% having sesamoid subluxation before surgery compared with 2.2% after (Table 2).

The mean HVA, IMA, and TSP preoperatively were 22.9°, 13.3°, and 4.6. The mean differences (95% confidence interval) in pre- and postoperative values were −14.9° (−16.3° to −13.4°) for HVA, −7.7° (−8.2° to −7.2°) for IMA, and −2.6 (−2.8 to −2.3) for TSP. Among bunions with MRA measurements, the mean difference was −12.3° (−14.5° to −10.0°). The DMAA decreased by −14.2° (−15.9° to −12.6°) (Table 3).

No infections or skin issues that altered the postoperative course occurred. No patients required a second operation for correction of a complication or recurrence (Figs. 1-3).

Table 1
Descriptive statistics

Variable	Value
Sex	
Male	5 (4.6)
Female	103 (95.4)
Side	
Right	60 (55.0)
Left	49 (45.0)
Healing	
Yes	109 (100)
No	0 (0)
Recurrence	
Yes	1 (0.9)
No	108 (99.1)
Months	17.4 (9.6)

Data are n (%) or mean ± standard deviation.

Table 2
Descriptive statistics

Variable	Preoperative	Postoperative
Lateral round sign		
Positive	93 (85.3)	0 (0)
Negative	16 (14.7)	109 (100)
Seiberg index		
Neutral	43 (82.7)	74 (86.0)
Dorsiflexed	4 (7.7)	3 (3.5)
Plantarflexed	5 (9.6)	9 (10.5)
Sesamoid subluxation		
Yes	24 (31.6)	2 (2.2)
No	52 (68.4)	89 (97.8)

Data are n (%).

Table 3
Descriptive statistics

Variable	n	Mean	Standard Deviation	95% Confidence Interval
HVA				
Preoperative	109	22.9	7.6	21.4 to 24.3
Postoperative	109	8.0	4.5	7.1 to 8.9
Change	109	−14.9	7.4	−16.3 to −13.4
IMA				
Preoperative	109	13.3	2.4	12.9 to 13.8
Postoperative	109	5.7	2.4	5.2 to 6.1
Change	109	−7.7	2.7	−8.2 to −7.2
TSP				
Preoperative	109	4.6	1.2	4.4 to 4.9
Postoperative	109	2.0	0.8	1.9 to 2.2
Change	109	−2.6	1.3	−2.8 to −2.3
MRA				
Preoperative	92	7.8	8.0	6.0 to 9.7
Postoperative	77	−4.5	6.8	−5.9 to −3.1
Change	72	−12.3	9.5	−14.5 to −10.0
DMAA				
Preoperative	109	19.6	9.2	17.8 to 21.3
Postoperative	109	5.3	3.8	4.6 to 6.1
Change	109	−14.2	8.7	−15.9 to −12.6

Abbreviations: DMAA, distal metatarsal articular angle; HVA, hallux valgus angle; IMA, intermetatarsal angle; MRA, metatarsal rotation angle; TSP, tibial sesamoid position.

Discussion

Over the past decade, multiple researchers have acknowledged a frontal plane component of HAV, which was first recognized decades ago (8–11). This third plane of the deformity is an extremely important component of complete and normal anatomic correction.

Okuda et al (5) associated metatarsal rotation with shape of the lateral first metatarsal head and found that patients who had a positive LRS on AP radiograph had a greater HVA and a greater chance of recurrence. In its anatomic 3D position, the metatarsal head is flattened medially and laterally on the AP radiographic projection. When pronation of the first metatarsal occurs, the round lateral plantar condyles are brought into profile, and their projection appears on the AP radiograph as the LRS. Okuda et al (5) concluded that the LRS is a marker of frontal plane rotation and therefore should be corrected intraoperatively. If LRS is present postoperatively, the risk of deformity recurrence is high because of failure of complete derotation to neutral position, which leaves the effective pull of the long and short flexors lateral to the midline of the effective axis of the first ray. During weightbearing, the hallux is then pulled lateral and exerts a net medial buckling force on the first metatarsal, opening the IMA (12). In our opinion, normalization of the LRS in our study (93 subjects with positive LRS preoperatively, 0 subjects postoperatively) was one of the factors associated with our low recurrence rate (0.9%). The reduction of the LRS came directly through intentional supination of the first metatarsal during the procedure.

The DMAA (also known in the literature as the proximal articular set angle, PASA), is commonly discussed in HAV literature. Although this measurement is typically seen as a separate component of the deformity, the reliability and even the existence of a true anatomic deformity associated with this measure has been debated. In an assessment of inter- and intraobserver reliability of radiographic angles by Coughlin and Freund (13), the HVA and intermetatarsal angle were validated, while there was questionable reliability of the DMAA. The DMAA as a reliable measurement of a deformity of the distal metatarsal surface has been a topic of discussion for years, with many finding the DMAA correlated with rotation of the hallux/sesamoids (14–16). Chi et al (14) specifically called into question the relevance of the DMAA because of poor agreement across observers in reduction of the DMAA after proximal metatarsal procedures. They concluded that rotation of the first metatarsal in the frontal plane may correlate with changes in the DMAA (14). Dayton et al (17) further found an 18.7° reduction of the PASA after TMT arthrodesis with frontal plane correction. The changes in the measured PASA correlated with derotation of the metatarsal in the frontal plane. It is clear from the analysis of the available literature that the reliability and clinical importance of the DMAA for evaluation of a deformity of the distal metatarsal surface is questionable at best. This is likely because radiographic DMAA/PASA assessments are a 2D observation of a 3D deformity of the first ray. This study reinforces the notion that DMAA is a radiographic artifact, as we observed a mean reduction of −14.2° (19.6° preoperative to 5.3° postoperative) without distal osteotomy or other joint manipulation.

The 3D position of the first metatarsal also affects the sesamoid position perceived on the AP radiograph. Okuda et al (18) studied the position of the sesamoids after a proximal osteotomy; initially, the IMA and HVA improved significantly. However, 3.1 to 45 months after surgery, there were significant increases in both the HVA and IMA, signifying recurrence. These increases in HVA and IMA were correlated with high preoperative and immediate postoperative TSP. To decrease the probability of recurrence, the sesamoids must be completely reduced intraoperatively. We have traditionally used capsular balancing to try to position the sesamoids; however, as this study pointed out, if there is metatarsal pronation, sesamoid position cannot be maintained with soft tissue procedures if the first metatarsal remains pronated. Shibuya et al (19) followed up with a study of their own that evaluated demographic data, preoperative severity of HAV, angular measurements of HAV, the amount of correction, and postoperative alignment for associations with recurrence. They found a >50% recurrence rate of HAV when the postoperative TSP was >4. This further confirms that to have extremely low rates of recurrence, complete correction of all planes of the deformity (including the frontal plane) is required. A study in 2017 by Dayton and Feilmeier (20) found that after patients underwent triplanar correctional arthrodesis, 100% had resolution of sesamoid subluxation without recurrence of the deformity. In this series, consistent reduction in MRA measured on axial projection along with the reported normalization of LRS confirmed supination or varus rotation of the first metatarsal during the procedure. Both of these factors are associated with our low recurrence rate at final radiographic assessment (0.9%). The intentional supination of the first metatarsal was also the factor that produced the correction of the TSP observed on the AP radiograph, since we did not do traditional capsular balancing to attempt to align the sesamoids, but instead relied on triplane correction to allow the sesamoids to remain anatomically aligned relative to the plantar first metatarsal head and bring them in line with the x-ray beam.

Sesamoid subluxation was present in 31% of our patients preoperatively and 2.2% postoperatively. This reinforces 2 important concepts regarding 2D evaluation of TSP on AP radiographs. First, despite the fact that our AP TSP had a mean of 4.6 preoperatively, which would suggest

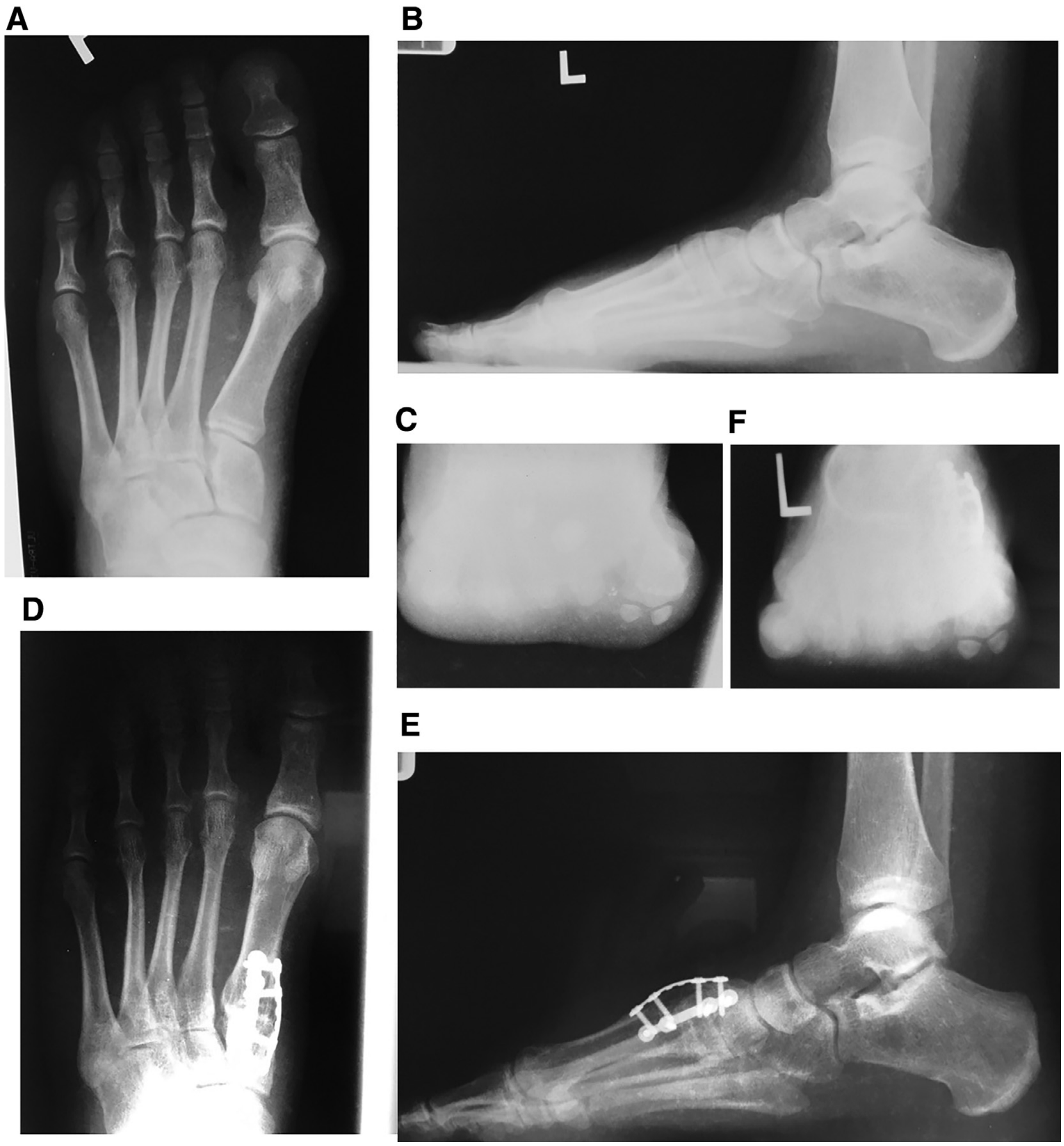

Fig. 1. Alignment of the right first ray and first MTPJ before and after tarsal metatarsal corrective arthrodesis. Triplane correction resulted in anatomic alignment of the right first MTPJ without distal procedures. Postoperative radiographs illustrate complete correction with no recurrence at 12 months. (*A*) Preoperative AP measurements of HVA, IMA, DMAA, and TSP were 30°, 14.7°, 24.7°, and 4, respectively. LRS was present preoperatively. (*B* and *E*) Postoperative lateral SI shows neutral alignment. (*C*) Preoperative axial measurement of MRA is 7.5° of pronation, and no sesamoid subluxation is noted. (*D*) Postoperative AP measurements using the anatomic axis of HVA, IMA, DMAA, and TSP were 0.8°, 3.1°, 4.2°, and 1, respectively. LRS correction was maintained postoperatively. (*F*) Postoperative axial measurement of MRA is 15° of supination, and absence of sesamoid subluxation was maintained. Abbreviations: AP, anterior-posterior; DMAA, distal metatarsal articular angle; HVA, hallux valgus angle; IMA, intermetatarsal angle; LRS, lateral round sign; MRA, metatarsal rotation angle; MTPJ, metatarsophalangeal joint; SI, Seiberg index; TSP, tibial sesamoid position.

subluxation, only 31% were actually subluxed relative to the plantar crista. This suggests that AP TSP may not be an accurate assessment of the true relationship between the sesamoids and the first metatarsal. Second, TSP was corrected to a mean of 2.0, which is well within the normal range without medial capsular plication, tendon transfers, or other soft tissue balancing maneuvers. Rotation provided correction of these positions, and soft tissue balancing was completed through deformity correction, not "capsular and tendon balancing."

This study demonstrates that 3D correction of HAV at the anatomic apex may be important for satisfactory postoperative outcomes with low rates of recurrence. The anatomic apex of the bunion deformity is at the TMT (21). Ortiz et al (22) predicted the angle necessary to correct the deformity, measuring the preoperative anatomic axis and the "predicted" anatomic axis of the first metatarsal. Dayton et al (23) then completed an anatomic analysis of HAV to identify the apex of the deformity at the first metatarsal cuneiform joint. This agrees with the work by Tanaka et al (24), who mapped the first ray and concluded the anatomic apex to be at the TMT, along with deviation of the MTPJ. It needs to be stated that these AP radiographic measurements are 2D, and we must look past these views alone to understand the true 3D alignment. Sesamoid axial views are a vital part of understanding the deformity and producing consistent correction. Our series confirms that triplane correction at the anatomic apex provides true correction of all parameters that we commonly measure.

When an osteotomy is chosen for correction of HAV, a new deformity is created in a normally anatomically straight first metatarsal. Unlike TMT triplane correction, the angulated metatarsal changes the normal first ray axis and cannot fully resolve the triplane deviations at the MTPJ and TMT, even with aggressive capsular manipulation. This also creates difficulty measuring postoperative angular differences

Fig. 2. Alignment of the right first ray and first MTPJ before and after tarsal metatarsal corrective arthrodesis. Triplane correction resulted in anatomic alignment of the right first MTPJ without distal procedures. Postoperative radiographs illustrate complete correction with no recurrence at 18 months. (*A*) Preoperative AP measurements of HVA, IMA, DMAA, and TSP were 26.5°, 18.2°, 28.7°, and 6, respectively. LRS was present preoperatively. (*B* and *E*) Postoperative lateral SI shows neutral alignment. (*C*) Preoperative axial measurement of MRA is 23.2° of pronation, and no sesamoid subluxation is noted. (*D*) Postoperative AP measurements using the anatomic axis of HVA, IMA, DMAA, and TSP were 6.5°, 3.7°, 3°, and 2, respectively. LRS correction was maintained postoperatively. (*F*) Postoperative axial measurement of MRA is 5° of supination, and absence of sesamoid subluxation was maintained. Abbreviations: AP, anterior-posterior; DMAA, distal metatarsal articular angle; HVA, hallux valgus angle; IMA, intermetatarsal angle; LRS, lateral round sign; MRA, metatarsal rotation angle; MTPJ, metatarsophalangeal joint; SI, Seiberg index; TSP, tibial sesamoid position.

between all of the first ray segments in a metatarsal that has been made crooked with an osteotomy. As discussed in the Introduction, the mid-diaphyseal line of the first metatarsal can no longer be used as a reference to measure IMA after osteotomy. It has become conventional to measure the angle based on points at the center of the MTPJ and TMT (i.e., mechanical axis) after osteotomy. However, this does not define the new position of the first metatarsal and other segments accurately: it is, in reality, a severe form of observation bias. This is illustrated by a 2018 study that confirmed that the foot width is either not changed or actually increases after osteotomy in the majority of cases (25). This is in distinction to their angular measurements using the center of joint method, which reported reduction in IMA.

Our series confirms that true deformity correction (normal triplane alignment) can be consistently achieved if the deformity is addressed at its anatomic apex. The IMA change of −7.7° (13.3° to 5.7°) confirmed in this series was based on the same preoperative and postoperative measurements. Although we could not compare and report overall osseous foot width measurements because radiographs were taken on different x-ray systems, the foot width did indeed consistently decrease. This is because true anatomic angular correction was made at the anatomic apex (TMT). In other words, the entire metatarsal was swung back into position to replicate the narrowest condition possible.

SI quantitatively measures the position of the first metatarsal relative to the second in the sagittal plane, with elevation indicated as a positive value. Samimi et al (26) found that an increase in SI postoperatively in HAV patients was a statistically significant variable in predicting an unsatisfied postoperative patient. Previous research has reported SI being on average twice as much in patients who have hallux limitus compared with HAV (26,27). An increase in the SI after TMT arthrodesis would indicate malpositioning of the first metatarsal in the sagittal plane, which could cause a hallux limitus and possibly other complications. Our results showed that 96.5% of metatarsals had a neutral or plantarflexed position value postoperatively, compared with 90.3% preoperatively, and no patient who was plantarflexed or neutral preoperatively had dorsiflexed values postoperatively. This indicates that we were able to get proper metatarsal positioning when completing our TMT arthrodesis while maintaining normal sagittal plane alignment.

Complete healing of the operative site, without hardware failure, is an important aspect of any arthrodesis procedure. Healing in this study was defined as a union with a progressive increase in radiodensity at the arthrodesis interface, absence of hardware loosening or failure, and maintenance of position (20). Evidence of motion between the osseous segments, failure of hardware, loss of position, and increased gapping or lucency at the fusion site indicates failure or delay of union. A previous study on the biplanar plating TMT arthrodesis construct used in this study found a 96.82% union rate and hardware failure/loosening in <1.85% of patients (28). Our results in this study are consistent with these results, as we had 100% of TMT joints heal with no cases of hardware failure.

We acknowledge that limitations to our experimental design may affect the presented conclusions and encourage readers to consider all potential bias and study limitations. This series was a retrospective review of a single surgeon's experience, which must be extrapolated to

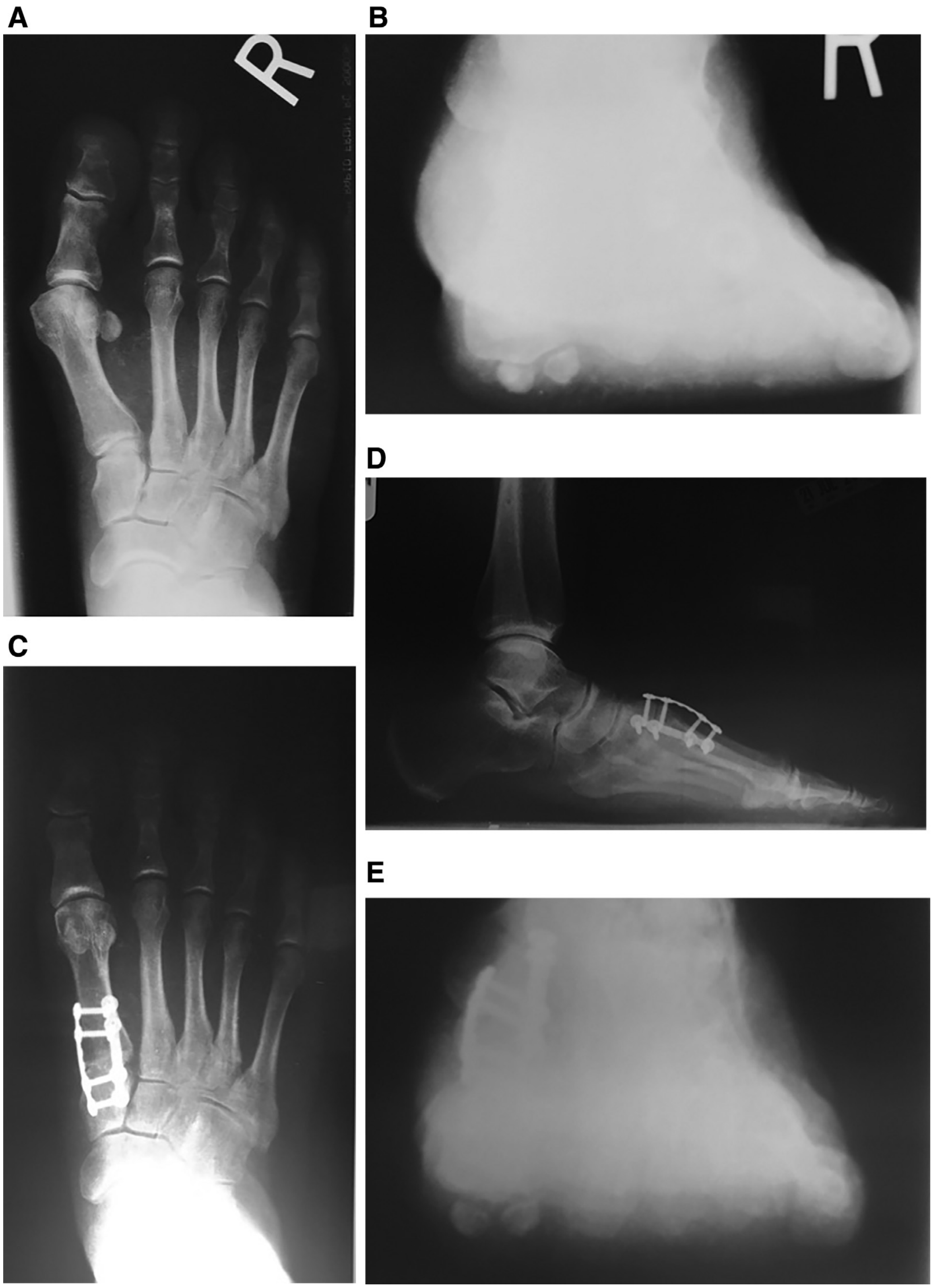

Fig. 3. Alignment of the right first ray and first MTPJ before and after tarsal metatarsal corrective arthrodesis. Triplane correction resulted in anatomic alignment of the right first MTPJ without distal procedures. Postoperative radiographs illustrate complete correction with no recurrence at 12 months. (*A*) Preoperative AP measurements of HVA, IMA, DMAA, and TSP were 28.6°, 16.7°, 31.2°, and 7, respectively. LRS was present preoperatively. (*B*) Preoperative axial measurement of MRA is 5.5° of pronation, and no sesamoid subluxation is noted. (*C*) Postoperative AP measurements using the anatomic axis of HVA, IMA, DMAA, and TSP were 2.2°, 6.8°, 4.7°, and 2, respectively. LRS correction was maintained postoperatively. (*D*) Postoperative axial measurement of MRA is 5.6° of supination, and absence of sesamoid subluxation was maintained. (*E*) Postoperative lateral SI shows neutral alignment. Abbreviations: AP, anterior-posterior; DMAA, distal metatarsal articular angle; HVA, hallux valgus angle; IMA, intermetatarsal angle; LRS, lateral round sign; MRA, metatarsal rotation angle; MTPJ, metatarsophalangeal joint; SI, Seiberg index; TSP, tibial sesamoid position.

the larger population of foot and ankle surgeons. Radiographic measurements have inherent variability that may affect the outcomes presented in any case series. Both digital and plain films were used in this retrospective review, which prevented comparison of some common findings such as osseous foot width. Although it was beyond the scope of this investigation, patient-reported outcomes are necessary to determine the overall success or failure of any surgical procedure.

In this study, radiographic outcomes of triplanar TMT arthrodesis were promising. Triplane TMT arthrodesis provided patients with robust and reliable correction of all planar components of the deformity, with low recurrence and low rate of healing problems at a mean of 17 months postoperatively. Further studies are necessary to examine long-term patient-reported outcomes.

Acknowledgments

The authors thank Lauren Hill, MS, Biostatistician, for her assistance with statistical analysis.

References

1. Pentikainen I, Ojala R, Ohtonen P, Piippo J, Leppilahti J. Preoperative radiological factors correlated to long-term recurrence of hallux valgus following distal chevron osteotomy. Foot Ankle Int 2014;35:1262–1267.
2. Coughlin MJ, Saltzman CL, Nunley JA. Angular measurements in the evaluation of hallux valgus deformities: a report of the ad hoc committee of the American Orthopaedic Foot & Ankle Society on angular measurements. Foot Ankle Int 2002;23:68.
3. Dayton PD, Dujela M, Egdorf RE. Recurrence and hallux varus. In: Dayton PD, ed. *Evidence-Based Bunion Surgery*, New York: Springer, 201891–112.
4. Gerbert J. *Textbook of Bunion Surgery*. WB Saunders, New York, 2001.
5. Okuda R, Kinoshita M, Yasuda TA, Jotoku T, Kitano N, Shima H. The shape of the lateral edge of the first metatarsal head as a risk factor for recurrence of hallux valgus. J Bone Joint Surg 2007;89:2163–2172.
6. Karthas TA, Cook JJ, Matthews MR, Sganga ML, Hansen DD, Collier B, Basile P, Cook EA. Development and validation of the foot union scoring evaluation tool for arthrodesis of foot structures. J Foot Ankle Surg 2017;57:675–680.
7. Vanore JV, Christensen JC, Kravitz SR, Schuberth JM, Thomas JL, Weil LS, Zlotoff HJ, Mendicino RW, Couture SD, S M; Clinical Practice Guideline First Metatarsophalangeal Joint Disorders Panel of the American College of Foot and Ankle Surgeons. Diagnosis and treatment of first metatarsophalangeal joint disorders. Section 1: Hallux valgus. J Foot Ankle Surg 2003;42:112–123.
8. Dayton PD. *Evidence-Based Bunion Surgery*. Springer, New York, 2018.
9. Kim Y, Kim JS, Young KW, Naraghi R, Cho HK, Lee SY. A new measure of tibial sesamoid position in hallux valgus in relation to the coronal rotation of the first metatarsal in CT scans. Foot Ankle Int 2015;36:944–952.
10. Hasenstein T, Meyr AJ. Triplanar quantitative radiographic analysis of the first metatarsal-phalangeal joint in the hallux abductovalgus deformity. J Foot Ankle Surg 2019;58:66–74.
11. Mizuno S, Sima Y, Yamaxaki K. Detorsion osteotomy of the first metatarsal bone in hallux valgus. J Jpn Orthop Assoc 1956;30:813–819.
12. Mortier JP, Bernard JL, Maestro M. Axial rotation of the first metatarsal head in a normal population and hallux valgus patients. Orthop Traumatol Surg Res 2012;98:677–683.
13. Coughlin MJ, Freund E. The reliability of angular measurements in hallux valgus deformities. Foot Ankle Int 2001;22:369–379.
14. Chi TD, Davitt J, Younger A, Holt S, Sangeorzan BJ. Intra- and inter-observer reliability of the distal metatarsal articular angle in adult hallux valgus. Foot Ankle Int 2002;23:722–726.
15. Lee KM, Ahn S, Chung CY, Sung KH, Park MS. Reliability and relationship of radiographic measurements in hallux valgus. Clin Orthop Relat Res 2012;470:2613–2621.
16. Robinson AHN, Cullen NP, Chhaya NC, Sri-Ram K, Lynch A. Variation of the distal metatarsal articular angle with axial rotation and inclination of the first metatarsal. Foot Ankle Int 2006;27:1036–1040.
17. Dayton P, Feilmeier M, Kauwe M, Hirschi J. Relationship of frontal plane rotation of first metatarsal to proximal articular set angle and hallux alignment in patients undergoing tarsometatarsal arthrodesis for hallux abducto valgus: a case series and critical review of the literature. J Foot Ankle Surg 2013;52:348–354.
18. Okuda R, Kinoshita M, Yasuda T, Jotoku T, Kitano N, Shima H. Postoperative incomplete reduction of the sesamoids as a risk factor for recurrence of hallux valgus. J Bone Joint Surg Am Ed 2009;91:1637–1645.
19. Shibuya N, Kyprios E, Panchani P, Martin LR, Thorud JC, Jupiter DC. Factors associated with early loss of hallux valgus correction. J Foot Ankle Surg 2018;57:236–240.
20. Dayton P, Feilmeier M. Comparison of tibial sesamoid position on anteroposterior and axial radiographs before and after triplane tarsal metatarsal joint arthrodesis. J Foot Ankle Surg 2017;56:1041–1046.
21. Paley D. *Principles of Deformity Correction*. Springer, New York, 2002.
22. Ortiz C, Wagner P, Vela O, Fischman D, Cavada D, Wagner E. “Angle to be corrected” in preoperative evaluation for hallux valgus surgery: analysis of a new angular measurement. Foot Ankle Int 2016;37:172–177.
23. Dayton P, Kauwe M, Feilmeier M. Is our current paradigm for evaluation and management of the bunion deformity flawed? A discussion of procedure philosophy relative to anatomy. J Foot Ankle Surg 2015;54:102–111.
24. Tanaka Y, Takakura Y, Kumai T, Samoto N, Tamai S. Radiographic analysis of hallux valgus. A two-dimensional coordinate system. J Bone Joint Surg Am 1995;77:205–213.
25. Tenenbaum SA, Herman A, Bruck N, Bariteau JT, Thein R, Coifman O. Foot width changes following hallux valgus surgery. Foot Ankle Int 2018;39:1272–1277.
26. Samimi R, Green DR, Malay DS. Evaluation of first metatarsophalangeal range of motion pre and post bunion surgery: a clinical and radiographic correlation with stress lateral dorsiflexion views. Podiatry Institute Update 2009:97–114.
27. Usuelli F, Palmucci M, Montrasio U, Malbera F. Radiographic considerations of hallux valgus versus hallux rigidus. Foot Ankle Int 2011;32:782–788.
28. Dayton P, Santrock R, Kauwe M, Gansen G, Harper S, Cifaldi A, Egdorf R, Eisenschink J. Progression of healing on serial radiographs following first ray arthrodesis in the foot using a biplanar plating technique without compression. J Foot Ankle Surg 2019;58:427–433.