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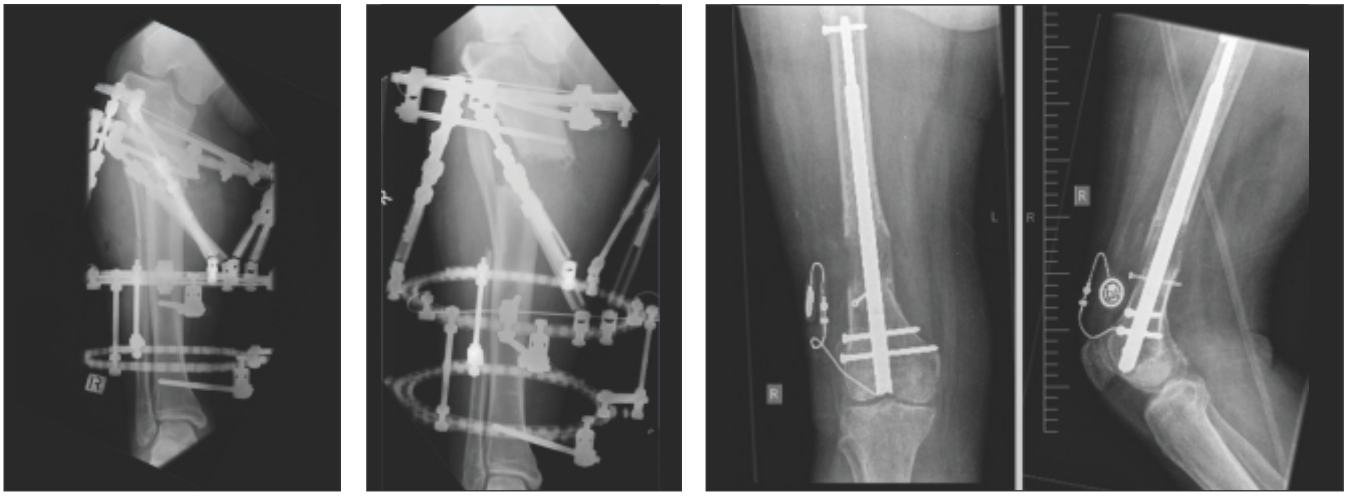

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Original Article

Distraction osteogenesis for brachymetatarsia: Clinical results and implications on the metatarsophalangeal joint

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Abstract

Background: Distraction osteogenesis (DO) using external fixation has revolutionized the management of brachymetatarsia, yet not without complications (30–100% incidence), the most common involving the metatarsophalangeal (MTP) joint.

Questions/Purposes: What are the clinical outcomes of DO for brachymetatarsia? What are the challenges and outcomes particularly related to the MTP joint? Does the method of stabilizing MTP joint during DO affect the outcome?

Materials and Methods: This is a retrospective study of 44 metatarsals (MTs) in 27 patients who underwent DO. Regarding MTP joint stabilization; 43% were fixed with K-wire across the joint, 32% with pinning of phalanges short of joint and attaching the K-wire to the external fixator, 7% by pinning of phalanges and distraction arthroplasty of the MTP joint, 2% no stabilization, and 16% by other methods. Clinical outcomes were analyzed by a nonvalidated 9-item questionnaire at the latest follow-up in addition to a review of postoperative radiographs. Complications, particularly pertaining to MTP joint were recorded.

Statistical Analysis: The paired *t*-test was used to assess the difference in MT length. Fisher's exact test used to evaluate rates of complications by MTP fixation method. McNemar's test was used to measure the difference in outcome questionnaire responses. Cochran–Armitage trend test was used to assess differences in toe-limitation before and after surgery.

Results: Postoperatively, MT length showed a significant increase of 12.98 ± 3.74 mm (28.55 ± 9.25%). Problems included MTP stiffness in 64%, MTP subluxation in 27%, and MTP dislocation in 7%, with no significant differences in outcome by MTP joint stabilization. Satisfaction with surgery was reported by 95% of patients.

Conclusion: DO is an effective treatment for brachymetatarsia, with high patient satisfaction. The most commonly reported problem was MTP joint stiffness with no functional deficit. There was no significant difference in the rate of MTP joint-specific complications by stabilization method. Larger patient numbers are required for validation of an optimal MTP joint stabilization method.

Level of Evidence: IV, Case Series.

Key Words: Brachymetatarsia, clinical results, complications, metatarsophalangeal joint

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Introduction

Brachymetatarsia is an abnormally short metatarsal (MT).[1] This is defined when one MT is 5 mm or more proximal to the parabolic arc of the MT heads.[2,3] The etiology of this condition could be either congenital or acquired due to premature closure of the physis,[4] trauma, surgery (iatrogenic), infection, tumor, or other specific disease.[5,6] Females are 5 times more affected than males, and bilateral involvement is observed in 72% of cases,[7] with the fourth ray being most commonly involved, followed by the first and fifth MTs, respectively.[8,9] Brachymetatarsia has esthetic, psychological, and functional implications. Patients commonly feel uncomfortable wearing open-toe footwear. In addition, disruption of the MT head parabola may lead to an inability of the affected short MT head to bear weight, with excessive weight distribution and increased loads occurring at the adjacent metatarsophalangeal joints (MTPs). This can lead to pain (transfer metatarsalgia), callosities, and difficulty wearing high-heeled shoes.[10,11]

While single-stage acute lengthening with interpositional bone graft and plate fixation has the advantages of instant gratification, the amount of length attainable is limited due to the risk of injury from the excessive tension acutely exerted on the neurovascular and musculotendinous structures of the foot.[3] Distraction osteogenesis (DO) using external fixation has had a significant impact on the management of brachymetatarsia.[12-14] The advantages of this method include the ability to achieve greater lengthening than with single-stage procedures, postoperative adjustability, avoidance of graft donor site morbidity, the possibility for simultaneous multiple MT lengthening procedures, and a lower incidence of neurovascular damage.[3,12,13,15,16]

Complications of DO in brachymetatarsia can be classified as major or minor. Major complications include malalignment of the MT, MTP joint dislocation or arthritis, nonunion, or callus fracture. Minor complications include pin tract infection, pin breakage, MTP joint subluxation, or stiffness.[13,16-18] The incidence of complications following DO for brachymetatarsia varies widely between studies and ranges from 30% to 100%.[1,3,4,19,20] Despite such variation, the most commonly reported complications are confined to the MTP joint.[1,11] No studies, however, have focused on the specific implications of DO on the MTP joint and the optimal fixation method during DO to avoid these complications.

The aim of this study is to answer the following questions: What are the clinical outcomes of DO for brachymetatarsia? What are the challenges and outcomes particularly related to the MTP joint? Does the method of stabilizing the MTP joint during DO affect outcome?

Materials and Methods

Statement of human subject testing

This retrospective case series study was approved by the Institutional Review Board (IRB) at the investigators' institution.

Patient selection and data collection

After IRB approval, a retrospective cohort of patients who had undergone DO for brachymetatarsia with a minimum follow-up of 1 year was identified. During the period from 4/2008 to 5/2013, a total of 44 MTs in 27 patients (2 males, 25 females), mean age 37.09 ± 13.98 years, who had undergone DO in our institution by the two most senior authors were included in this study. Inclusion criteria were patients between 18 and 60 years with brachymetatarsia. This included patients with esthetic and functional impairment and the presence of metatarsalgia, painful cock-up short toe, relatively good MTP joint mobility (>40° total MTP arc of motion) and the absence or minimal arthritis in the MTP joint of the short MT. Patients were excluded for an inability to comply with postoperative external fixator frame pin care and rehabilitation protocols and mental/physical comorbidities or reading disabilities that would prevent patients from answering functional questionnaires.

Surgical technique

The surgical technique for all cases followed a standard approach as previously reported.[21] Briefly, spinal anesthesia was given, and the patient was placed in the supine position without a tourniquet. Under fluoroscopic guidance, four mini-Schanz half-pins were placed in the MT with the monolateral mini-external fixator slots as guides. The first pin was placed in the base of the MT through a stab incision perpendicular to the longitudinal axis of the metatarsus in the sagittal plane. Care was taken to avoid the course of the long extensor tendons. The orientation of this first pin set the position of the frame which was placed parallel to the MT to ensure proper bone alignment in the sagittal plane during lengthening. After placement of all four half-pins and confirming position with intraoperative fluoroscopy, the external fixator was removed. A low-energy, mid-diaphyseal transverse osteotomy was performed with a 4 mm osteotome after predrilling with a 1 mm K-wire half way between the two clusters of mini-half-pins in the center of the MT bone.[1,22] If the extensor and flexor tendons were found to be tight intraoperatively then a simultaneous flexor and extensor tenotomy were performed to decrease tension to help avoid MTP joint subluxation/dislocation. The flexor digitorum longus (FDL) was released at the proximal flexor crease of the toe at the proximal interphalangeal joint. The extensor digitorum longus (EDL) and extensor digitorum brevis (EDB)

were released through the 1 cm incision made for the MT osteotomy. After confirmation of complete displacement of the osteotomy under fluoroscopy, closure of the subcutaneous tissue and skin was performed using 3-0 monocryl and 4-0 nylon, respectively. The mini-external fixator was then mounted on the pins, and final position of the bone is confirmed. The mini frame that we use is a single unit with the pin clamps and the rail all 1 unit. We find it best to remove the frame from the pins, perform the osteotomy and leave it nondisplaced, and then reapply the rail frame. The pins have all been placed in a uniplanar fashion, so this is not difficult. Lengthening was done by distracting at a rate of 0.5 mm/day (1/8 turn 4 times per day or ¼ turn 2 times per day) starting at postoperative day 7. Follow-up radiographs were obtained every 2 weeks. The frame was removed upon reaching the desired MT length and consolidation of three out of four cortices of the lengthened MT.

Prophylactic measures to prevent subluxation/dislocation of the MTP joint included: (1) Fixating the MTP joint with a 0.045 K-wire driven from the distal phalanx proximally into the MTP joint,[23] (2) spanning the MTP joint with an additional external fixator that was piggy-backed off the first DO frame on the MT side and placing mini-Schanz half-pins in the proximal phalanx to distract the MTP joint (distraction arthroplasty),[14,24] (3) pinning of phalanges without crossing the MTP joint and attaching the K-wire to the frame. There were other selected techniques (mainly fusion of 1st MTP joint after failed hemiarthroplasty [HAP] or avascular necrosis [AVN] hallux valgus surgery) and in some cases no stabilization of the MTP joint [Figure 1].

Clinical and functional outcomes

Range of motion of the affected MTP joint was objectively assessed before and after surgery by the most senior authors. In addition, observations, particularly pertaining to the MTP joint were recorded. This data were extracted from chart review of the latest follow-up visit. In addition, a nonvalidated 9-item questionnaire was administered to all patients as a part of our standard of care during their latest follow-up visit. This simple questionnaire was used as a subjective guide to clinical outcomes of the DO procedure [Table 1]. Time to healing was defined as the time in the frame. The healing index is the month per cm to healing. This is the same external fixation index which is months in frame per cm of healing.

Radiographic outcomes

Standard weight-bearing X-rays of the foot (anteroposterior [AP], lateral) and nonweight bearing oblique views were obtained pre- and postoperatively. The desired length was determined by using the second MT as the focal point for an arc to be drawn on the AP radiograph establishing the MT parabola, then determining the length needed from the distal aspect of the affected fourth or first MT to reach the parabola.[3,23] Alternatively a line drawn from the tip of the third MT to the tip of the fifth MT was drawn, and the distance from the tip of the fourth MTP to reach this line was measured. In a case of the first brachymetatarsia, a reference was made off of the third MTP as the length of the first and third MTs should be the same. All measurements were recorded using the picture archiving and communication system (PACS, Philips Easy Vision Healthcare, Bothell, WA, USA). All

Figure 1: (a) Anteroposterior and lateral weight-bearing radiographs of three different cases of DO for brachymetatarsia demonstrating three different methods of metatarsophalangeal stabilization. (a and b) Fixation with K-wire traversing the metatarsophalangeal joint. (c and d) Distraction arthroplasty of the metatarsophalangeal joint with a second mini-frame piggy-backed off the distal part of the metatarsal distraction frame (e and f) fixation with a K-wire traversing the proximal and distal interphalangeal joints (proximal interphalangeal and distal interphalangeal joints) but short of the metatarsophalangeal joint

radiographic measurements were performed by a foot and ankle fellowship-trained orthopedic surgeon.

All radiographic measurements, as well as the final aforementioned subjective and objective data were plotted on an excel worksheet (Microsoft, Redmond, WA, USA).

Statistical analysis

Statistical analysis was performed on radiographic measurements to assess the difference in MT length on plain X-rays from pre- to postoperative time point. The Shapiro–Wilk test was not significant for these variables, so the paired *t*-test was used to perform the comparisons. Fisher's exact test was used to evaluate rates of complications by MTP fixation method. For the outcome questionnaire, change in the proportion of patients who responded positively to the questions before surgery compared to after surgery were analyzed using McNemar's Test. For toe motion limitation, the Cochran–Armitage trend test was used to examine the proportion of patients who reported less limitation after surgery by the preoperative severity of the limitation. Statistical significance was set at $P < 0.05$. All analyses were performed using SAS software version 9.3 (SAS Institute, Inc., Cary, NC, USA).

Results

Patient demographics

The etiology of brachymetatarsia was congenital in 37 MTs, iatrogenic in 6 MTs (avascular necrosis [AVN] and bone loss following failed hallux valgus surgery and first MTP HAP) and posttraumatic (MT fracture nonunion with bone loss) in 1 MT. Seven patients had bilateral single ray involvement on each foot (14 MTs) while 3 patients had two affected rays on each foot (12 MTs). None of these patients had Apert or Turner syndrome. The fourth MT was affected in 26 cases (59.1%), the first MT in 10 cases (22.7%), the third MT in 4 cases (9.1%), the fifth MT in 3 cases (6.8%), and the second MT in 1 case (2.3%). Twelve cases (27.2%) had simultaneous extensor and flexor tenotomies with the DO procedure. Stratification of patients according to MTP stabilization method is summarized in Table 2. Mean time to follow-up was 14.71 ± 20.34 months. Time in external fixator was 4.22 ± 2.32 months. Mean time for MTP fixation/distraction was 2.33 ± 2.05 months. Time to healing, which was the same as total time in the frame, was 3.83 ± 2.5 months. Mean healing index was 3.32 ± 2.4 months/cm (99.6 ± 72 days/cm).

Clinical and functional outcomes

The 9-item questionnaire administered at the latest follow-up postoperative visit revealed that there was a significant difference in the proportion of patients who felt comfortable wearing open toe shoes in public ($P < 0.0001$) and standard shoes ($P < 0.022$) after surgery compared to before surgery. Excluding patients who had a first MTP fusion, toe stiffness after surgery was markedly noticeable and reported by 40% of patients. When classifying MTP joint ROM postoperatively into same/better versus worse, there was a statistically significant trend toward MTP joint ROM limitation postoperatively ($P = 0.004$), denoting an increased incidence of postoperative MTP stiffness. Although we observed some increased stiffness at the joint on physical examination, improved or same function was reported by 85% of patients on the 9-item questionnaire. Satisfaction with surgery and feeling that they would do it again was reported by 95% of patients.

Outcomes of the MTP joint, excluding patients who had an MTP fusion, are presented in Table 3. Twenty-eight of 37 cases (75.7%) were objectively found to have MTP stiffness on physical examination; 12/37 (32.4%) had MTP subluxation, and 3/37 (8.1%) had MTP dislocation. There were no statistical differences in the rate of these outcomes by MTP fixation method ($P > 0.05$ for all analysis). Thus, we were not able to demonstrate a difference in the outcome of

Table 1: The 9-item questionnaire administered to patients as part of our standard of care during their latest follow-up visit and used as a subjective guide to clinical outcomes of the DO procedure

Question	Answer
1. Did you feel comfortable wearing open toe shoes in public before surgery?	Yes/no
2. Do you feel comfortable wearing open toe shoes in public after surgery?	Yes/no
3. Did you feel comfortable wearing standard shoe wear before surgery?	Yes/no
4. Do you feel comfortable wearing standard shoe wear after surgery?	Yes/no
5. Did you have any limitation in the affected toe motion before surgery?	None/mild/ moderate/severe
6. Do you have any limitation in the operated toe motion after surgery?	Yes/no
7. Are you pleased with the outcome of your toe surgery?	Yes/no
8. If you knew then what you know now, would you do the surgery again?	Yes/no
9. How would you compare your function after surgery compared to before surgery?	Same/better/ worse

DO: Distraction osteogenesis

Table 2: Stratification of patients according to method of MTP stabilization

Patient count (*n*)	Percentage	Method of MTP stabilization
19	43.2	K-wire pinning across MTP joint
14	31.8	Pinning of phalanges short of MTP and attaching K-wire to the mini-external fixator
3	6.8	Pinning of phalanges and distraction arthroplasty of the MTP joint
1	2.3	No stabilization
7	15.9	Other methods (fusion of first MTP joint after failed HAP or AVN with bone loss)

MTP: Metatarsophalangeal, HAP: Hemiarthroplasty, AVN: Avascular necrosis

DO based on the method for stabilizing the MTP joint. This is likely related to small numbers in each type of stabilizing method. There was an evolution in our practice of MTP stabilization and it is our current impression that spanning the MTP joint with a second fixator provides the best method for protecting the joint. With additional patients and longer follow-up, we hope to be able to demonstrate this point with data in a future study. Six cases required additional surgeries which are described in detail in Table 4.

Complications affecting the lengthened MT are detailed in Table 5. There were no MT nonunions or refractures. There were two cases of premature consolidation; one was treated with repeat osteotomy and DO and the other was left alone as the patient was satisfied with the length attained and the esthetic appearance of the MT. There were 8/44 cases (18.18%) of malunion, four with lateral angulation and four with medial angulation of the involved MT of a mean of 6.2° ±1.63°. This did not have significant implications on the final esthetic appearance or functional outcome of the lengthened MT and all cases were satisfied and did not require further management. Pin tract infections occurred in 12/44 MTs (27.2%) and resolved in all patients with a course of oral antibiotics.

Radiographic outcomes

Preoperatively, there was MT shortening of 13.2 ± 3.51 mm or 28.96 ± 9.04% in relation to the normal MT length. Postoperatively, MT length increased from 46.34 ± 4.89 mm to 59.30 ± 5.10 mm with an increase of 12.98 ± 3.74 mm (28.55 ± 9.25%) ($P < 0.0001$). The parabola was restored in 75% cases. The remaining 25% of lengthened MTs were within 1–2 mm of the parabolic arch,

Table 3: Outcomes affecting MTP joint in different groups according to method of MTP stabilization during DO

MTP fixation method	Overall		No MTP stabilization		Pinning across MTP		MTP distraction		Pinning short of MPT + K-wire attach to frame	
	Count	Percentage	Count	Percentage	Count	Percentage	Count	Percentage	Count	Percentage
MTP arthritis										
Present	28	85.7	1	100.0	9	47.4	1	33.3	7	50.0
Absent	16	14.3	0	0.0	10	52.6	2	66.7	7	50.0
MTP subluxation/dislocation										
Dislocation	3	0.0	1	100.0	0	0.0	0	0.0	2	14.3
Subluxation	12	0.0	0	0.0	8	42.1	1	33.3	3	21.4
Absent	22	100.0	0	0.0	11	57.9	2	66.7	9	64.3
MTP stiffness										
Present	28	85.7	1	100.0	15	79.0	3	100.0	9	64.3
Absent	9	14.3	0	0.0	4	21.1	0	0.0	5	35.7

	No MTP stabilization		Pinning across MTP		MTP distraction	Pinning short of MTP+K-wire attached to frame			*P*
	Count	Percentage	Count	Percentage	Count	Percentage	Count	Percentage	
MTP arthritis									
Present	1	100	9	47.4	1	33.3	7	50	1.000
Absent	0	0	10	52.6	2	66.7	7	50	
MTP subluxation/dislocation									
Dislocation	1	100	0	0	0	0	2	14.3	0.132
Subluxation	0	0	8	42.1	1	33.3	3	21.4	
Absent	0	0	11	57.9	2	66.7	9	64.3	
MTP stiffness									
Present	1	100	15	79	3	100	9	64.3	0.631
Absent	0	0	4	21.1	0	0	5	35.7	

No statistically significant differences were found between groups. MTP: Metatarsophalangeal, DO: Distraction osteogenesis

Table 4: Obstacles that were treated surgically after DO for brachymetatarsia in 6 patients. These obstacles were completely resolved with the hereunder surgeries. None of the cases required further surgery and all 6 patients were satisfied with the procedure

Patient	Obstacle	Management
1	Fourth MTP flexion contracture + fourth hammertoe	MTP arthrotomy and capsular release, flexor tenotomy + PIP resection arthroplasty and smart toe implant
2	Fourth MTP extension contracture + fourth hammertoe	Fourth extensor tenotomy with removal of frame
3	First MTP extension contracture	First MTP arthrotomy and capsular release + extensor tenolysis and plantar plate release + MUGA
4	Fourth MTP stiffness + arthritis	Fourth MTP distraction arthroplasty + ICBMA injection
5	Fourth MTP stiffness + flexion and abduction contracture (cross-over toe)	Fourth MTP arthrotomy + capsular release + lateral collateral ligament release + pinning
6	Third MTP extension contracture	Third MTP arthrotomy and capsular release + extensor tenotomy

DO: Distraction osteogenesis, MTP: Metatarsophalangeal, PIP: Proximal interphalangeal, ICBMA: Iliac crest bone marrow aspirate, MUGA: Manipulation under general anesthesia

Table 5: Complications affecting the lengthened MT in different groups according to method of MTP stabilization during DO

MT fixation method	No MTP stabilization		Pinning across MTP		MTP Distraction		Pinning short of MTP + K-wire attached to frame		Other		*P*
MT complication (yes/no)	Count	Percentage	Count	Percentage	Count	Percentage	Count	Percentage	Count	Percentage	
Delayed consolidation											
No	1	100	19	100	3	100	13	92.86	5	71.4	0.149
Yes	0	0	0	0	0	0	1	7.14	2	28.6	
Malunion of MT											
No	1	100	14	73.68	3	100	11	78.57	7	100	0.665
Yes	0	0	5	26.32	0	0	3	21.43	0	0	
Premature consolidation											
No	1	100	18	94.45	3	100	13	92.85	7	100	0.25
Yes	0	0	1	5.55	0	0	1	7.14	0	0	
Pin tract infection											
No	1	100	14	73.68	1	33.3	12	85.71	4	57.1	0.294
Yes	0	0	5	26.32	2	66.7	2	14.29	3	42.9	

No statistically significant differences were found between groups. DO: Distraction osteogenesis, MT: Metatarsal, MTP: Metatarsophalangeal

and there was no significant difference in mean MT length gained postoperatively compared to the MT length calculated on preoperative films and required to achieve to restore the parabola ($P = 0.688$). Radiographic evidence of MTP arthritis of the involved lengthened MT was noted on the last follow-up in 18/44 cases (40.9%).

Discussion

Brachymetatarsia has been initially managed by acute lengthening and bone grafting. This technique, however, has its inherent limitations which include; limited lengthening obtained acutely due to insufficient yielding of the soft tissue envelope and neurovascular compromise, the morbidity of bone graft harvest and the open nature of the procedure for plate fixation. DO has overcome most of these aforementioned limitations yet not without inherent challenges. These can be classified as problems, obstacles, and complications. Problems are anticipated adverse results that arise but resolve by the end of treatment without additional surgery. Obstacles are anticipated adverse results that require surgical intervention but resolve by the end of treatment. Complications are local or systemic adverse results whereby their associated sequelae remain unresolved at the end of treatment.[17] The most reported complications of DO for brachymetatarsia in literature pertain to the MTP joint.[1,11] There has been no study up to date, which has investigated the effect of different methods of MTP stabilization during DO for brachymetatarsia on the incidence of MT-specific outcomes of the procedure.

In this study, we sought to answer three questions. What are the clinical outcomes of DO for brachymetatarsia? What are the outcomes particularly related to the MTP? Does the method of stabilizing MTPs during DO affect the outcome?

There are a number of limitations to this study. First, it is retrospective in nature with a limited number of patients, which might account for the insignificant difference in complication rates specific to the MTP joint per method of fixation. It is worth mentioning that the incidence of congenital brachymetatarsia is less than 1/1000 (approximately 0.02–0.05%),[25] which makes obtaining enough patients for achieving larger numbers per fixation method relatively challenging. Another limitation was the utilization of a nonvalidated 9-item questionnaire for assessment of functional outcomes. Until the time of initiation of this study, none of the current foot and ankle scores or questionnaires had been specifically validated for the assessment of brachymetatarsia. While utilizing commonly used foot and ankle scores as the AOFAS score reported in other studies might aid in drawing comparisons, yet the insignificant value of utilization of a nonvalidated score that would not detect significant outcomes of the procedure is an argument for substituting it with a simple questionnaire that is, easy to fill out in a reasonable time and cost-effective manner. Lee *et al*.[26] utilized the AOFAS score in evaluating three different surgical techniques for the treatment of brachymetatarsia. Although patients reported a statistically significant difference in the rate of satisfaction between two of the three different procedures, the mean postoperative AOFAS scores were similar in all the three groups.

There are a number of strengths to the current study. To the authors' knowledge, this is, the first study aiming at specifically analyzing the clinical and radiological complications pertaining to the MTP joint after brachymetatarsia DO. Moreover, it is the first study to report on the effect of the method of stabilization used for the MTP joint and its effect on the outcome of DO. The self-reported patient questionnaire devised by our practice helps to illustrate overall patient satisfaction with the procedure from both functional and esthetic/psychological viewpoints, despite the challenges observed at the MTP joint.

Several studies have reported on clinical and radiological outcomes of the fourth and first brachymetatarsia, yet most of them are case reports with a limited number of cases.[18,20,27,28] In terms of clinical outcomes, most of these studies report only subjective outcomes and a few give objective clinical results.[3,4,19,29,30] Our clinical results demonstrate that improved or same function was reported by 85% of patients, and satisfaction with surgery was reported by 95% of patients. This is in accordance with other studies; Kim *et al*.,[3] Lee *et al*.,[11] and Oh *et al*.[4,19] reported 80%, 97%, and 100% good or excellent results for the first brachymetatarsia, respectively. The same authors reported 80%, 95%, and 89% good or excellent results for the fourth brachymetatarsia, respectively.

Healing index was reported in our study to be 99.6 ± 72 days/cm, which is equivalent to what has been reported in literature in a multitude of studies where the mean healing indices for DO have been reported, ranging from 60.0 to 98.0 days/cm for patients with the first brachymetatarsia and 43.4 to 82.0 days/cm for patients with the fourth brachymetatarsia, with a mean percentage gain in length ranging from 31% to 52%.[3,4,6,12,16,18,20,23,30]

Regarding MTP outcomes, our results show that MTP stiffness was the most common problem pertaining to the MTP joint after DO. Oh *et al*.,[4,19] Lee *et al*.,[11] and Masada *et al*.[18] reported decreased ROM of the MTP joint in all cases postoperatively. While only 40% of patients in our study reported a markedly noticeable limitation in ROM of their MTP joints postoperatively, objective clinical examination revealed 64% patients had MTP stiffness, defined as 50% reduction in ROM compared to preoperative levels.[31] This is relatively higher than what is reported in other studies, which showed a wide variability in this complication, together with ambiguity in defining it and combining it with other complications of the MTP joint. Kim *et al*.[3] reported a relatively low MTP stiffness rate of 5%. Combined MTP stiffness and subluxation was reported in 17.9% and 33.7% in Shim and Park[16] and Lee *et al*.'s[11] studies, respectively. Masada *et al*.[18] and Lee *et al*.[26] reported a relatively higher MTP stiffness rate of 30% and 44.4%,[1] respectively. While Takakura *et al*.[20] observed an MTP stiffness rate of 50%, they noted this was increased when lengthening exceeded 40% of the preoperative length of the MT. Our findings do not support this finding in 5/6 cases (83.3%) in our series who underwent lengthening of more than 40% developed MTP stiffness, as opposed to 28/38 cases (73.6%) with < 40% lengthening. Our results also showed 27.2% subluxation and 6.8% dislocation rates. Again, this was slightly higher for subluxation than found in other studies that reported on such complication, but equivalent rates of dislocations were found; Erdem *et al*.[32] reported 1 case of subluxation (7.1%) in their series of 14 MTs, while Magnan *et al*.[8] reported on 1 case of subluxation (11.1%), and another of dislocation (11.1%) in their series of 9 patients. Wada *et al*.[6] also reported a single case of MTP dislocation (8.3%) in their series of 12 MTs. Finally, our results did not show significant differences in the outcome by MTP fixation method, which again, is most likely attributable to the small number of MTs per group.

Radiographic outcomes showed that the parabola was restored in 75% cases with the remaining 25% falling within 1–2 mm short of the parabola. Preoperatively, there was MT shortening of 28.96 ± 9.04% in relation to the normal MT length. Postoperatively, MT length increased 12.98 ± 3.74 mm (28.55 ± 9.25%). Radiological evidence of MTP arthritis of the lengthened MT was noted in 40.9% cases. MTP stiffness and arthritis after DO may be due to a number of reasons; excessive lengthening of the MT creates tension in the lengthened tendons and the peri-articular structures traversing the joint, as well as the joint capsule itself. Such tension might exceed the remodeling limits of these structures in a manner disproportionate to tension remodeling in the lengthened bone, which ultimately leads to increased MTP joint contact pressures that predispose to stiffness and subsequent arthritis. MTP joint stiffness and arthritis can also occur secondary to joint subluxation/dislocation with incongruency and altered joint contact pressures. It can also occur iatrogenically from prophylactic stabilization of the MTP joint with temporary K-wire fixation, which might initiate a cascade of inflammatory events that may lead to the progression of the degenerative changes, particularly with repeated pinning attempts and generation of thermal necrosis associated with closed drilling across the joint. Another important factor in the development of MTP arthritis after distraction is determined by the final position of the MT head after lengthening. We were very critical in our evaluation of the joint. Subluxation was reported when the joint had any change in congruity. There is a lot of pressure generated on the MTP joint during these lengthening. Our current practice is to release FDL, EDL, EDB, and span, distract, and stabilize the joint for as long as tolerated even the full time in the frame. We feel that systematic release of tendons is indicated and that it decreases the soft-tissue strain and likely the pressure across the joint.

Frames placed dorsally parallel to the longitudinal axis of the MT shaft in the sagittal plane rather than parallel to the ground aid in bringing the MT head plantarly with lengthening. We orient the frame between the long axis of the MT and the line

parallel to the ground. While this ultimately aids in bearing more loads by the head of the lengthened MT and takes a load off the overloaded adjacent MTs with relief of metatarsalgia, inadvertent excessive lengthening may lead to increased plantar displacement of the MT head, leading to excessive MTP joint loading, increased contact pressures, and subsequent arthritis. We have not noticed apex dorsal bony deformity as a significant problem.

A distraction rate of 1/8 turns 4 times per day for a total of 1.2 mm per day is used by our practice. This has resulted in optimal healing of the MTs and seems to work well considering that these are high percentage lengthening with the large strain on the soft tissues. Although integrated fixation like lengthening over a nail has been useful in long bones, it does not seem to apply to MT lengthening. We do not have useful internal fixation such as a locking intramedullary nail, and the bone diameter is so limited. Overall, bone healing and time in the frame have not been a problem.

Conclusion

This study further demonstrates that DO provides an effective treatment option for brachymetatarsia, with high patient satisfaction rates despite challenges. The most commonly reported problem was MTP stiffness, which concurs with what was previously reported in literature, and does not seem to affect the overall satisfaction with the procedure. MTP obstacles were successfully managed with further surgery. There was no significant difference in the rate of MTP-specific outcomes by MTP fixation method, likely due to the small sample size per method of fixation. Although several techniques have been described for prevention and management of MTP complications, there still remain a lack of a consensus on the optimal technique and a dearth of evidence to support any one method. Larger patient numbers with longer follow-up periods are still required for further validation of the optimal method of MTP stabilization. Our impression is that the optimal method for MTP joint protection is spanning the joint with a distraction frame. This is our current practice.

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Conflicts of interest

Dr. Fragomen reports personal fees from Smith and Nephew Inc., outside the submitted work. Dr. Rozbruch reports personal fees from Smith and Nephew Inc., and personal fees from Small Bone Innovations Inc., outside the submitted work. Ms. Do reports grants from Clinical and Translational Science Center, outside the submitted work.

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