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Comparison of screw-fixation stabilities of first metatarsal shaft osteotomies: a biomechanical study

A. Meriç ÜNAL, Önder BARAN, Bora UZUN,* Ahmet C. TURAN

*Departments of Orthopedics and Traumatology and *Biomechanics, Medicine Faculty of Dokuz Eylül University, İzmir*

Objectives: Although metatarsal shaft osteotomies have become popular in the surgical treatment of moderate or advanced hallux valgus owing to better reduction and stability, they present fixation problems as the angular correction increases. The purpose of this biomechanical study was to evaluate the effects of widely used metatarsal shaft osteotomies and a newly defined osteotomy modification on the stability of screw fixation at greater angular corrections.

Methods: Upon evaluation of known problems of shaft osteotomies, a new osteotomy type was designed that might provide an adequate contact area while allowing a greater angular correction, increased stability, and safer osteosynthesis. In our new modification of the Mau osteotomy, the proximal plantar notch that was defined for the Sammarco's modification to increase the contact area was created more proximally making an angle of about 50 degrees with the osteotomy, and the osteotomy was extended until 5 mm to the distal joint surface, aiming to increase the contact area and intrinsic stability. For biomechanical analysis, 30 standard metatarsal bone models (Sawbones) were divided into five groups equal in number for the following osteotomy methods: Myerson's modification of the Ludloff osteotomy, Mau osteotomy, scarf osteotomy, offset V osteotomy, and the new modification of the Mau osteotomy. Osteotomies were performed with a standard correction of 10 degrees in the intermetatarsal angle, followed by appropriate osteosynthesis with fixation by two Acutrak compression screws. The relationship between osteotomies and osteosynthesis in terms of stability was assessed by the three-point bending test.

Results: The mean stiffness of the Ludloff osteotomy was significantly lower than all the other osteotomy groups ($p<0.05$). Stiffness of the Mau group was significantly greater than three groups ($p<0.05$), but the difference from the offset V group did not reach significance. Stiffness of the new Mau modification was significantly greater than the scarf group ($p=0.016$), but did not differ significantly from the offset V group. Osteotomy groups with and without notching had similar stiffness values ($p=0.582$), whereas single notching was associated with a significantly greater stiffness compared to double notching ($p=0.031$).

Conclusion: Our findings suggest that the new modification to the proximal shaft osteotomies moves the center of rotation of angulation more proximally and provides sufficient stability of screw fixation.

Key words: Biomechanics; hallux valgus/surgery; metatarsal bones/surgery; osteotomy/methods.

Hallux valgus is the most common foot deformity characterized by lateral deviation of the great toe and medial deviation of first metatarsal.[1-3] Extrinsic and intrinsic factors are thought to play role in its etiology and it is more prevalent in females.[1,3] The most frequently used evaluation parameters are the hallux valgus angle and the intermetatarsal angle.[3-10] Current classification is based on radiographic measure-

Correspondence: A. Meriç Ünal, MD. Sanayi Mah., İstanbul Cad., Ali Münif Özdemir Apt.,No: 52, Kat 2 D: 1, 32200 Isparta, Turkey.
Tel: +90 246 - 223 73 16 e-mail: abdmunal@yahoo.com

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ments and classifies the disease as mild, moderate, and severe.[3,7]

The only treatment to correct deformity is surgery. Considerations for technical choice include the hallux valgus angle, intermetatarsal angle, arthritis in the first metatarsophalangeal joint, hypermobility of the first tarsometatarsal joint, position of sesamoids, muscle-tendon balance, and congruity of the first metatarsophalangeal joint.[5] Surgical techniques are generally classified as soft tissue procedures, metatarsal and phalangeal osteotomies, and combinations thereof.

The main objective of metatarsal osteotomies is to decrease the intermetatarsal angle. Distal, shaft, and proximal osteotomies have been defined based on the osteotomy site. In general, distal osteotomies are used in mild and moderate cases, and proximal osteotomies in severe cases.

Metatarsal shaft osteotomies have been recognized since 1920s and become more popular with recent modifications. The most commonly used types are the Ludloff, Mau, scarf osteotomies, and offset V osteotomy as a modification of the distal chevron osteotomy.[11-16] All these osteotomies have been thought as not being ideal and new modifications have been made.[11-15] These modifications mainly focus on efforts to increase contact surface, improve union and osteotomy stability, decrease shortening, dorsal angulation, and osteotomy-related complications, and to widen the indications.[11-17]

In our clinic, we developed a new modification to the Mau osteotomy and incorporated the following features into the technique: *(i)* The plane of the osteotomy was made parallel to the plantar surface. *(ii)* The straight line of the Mau osteotomy was terminated proximally adding an L-shaped curve whose angle faced the plantar surface. *(iii)* The rotation center was moved to the proximal. With this newly defined modification, we aimed to achieve both a better reduction and a more stable fixation.

Although two-screw fixation is the most reliable technique compatible with the principles of osteosynthesis, several technical problems arise following osteotomies with regard to screw placement. The main drawback is that increased angular correction results in decreased contact area.

The purpose of this biomechanical study was to evaluate the effect of greater angular corrections obtained by widely used metatarsal shaft osteotomies and the newly defined modification of the Mau osteotomy on the stability of screw fixation.

Materials and methods

In this study, 30 standard bone models of the left first metatarsal made up of solid foam were used (Sawbones, Malmö, Sweden). The models were divided into five groups equal in number for the following osteotomy methods to be performed: Myerson's modification of the Ludloff osteotomy,[13] Mau osteotomy,[12] scarf osteotomy,[11] offset V osteotomy,[11] and the new modification of the Mau osteotomy (Fig. 1).

In our new modification of the Mau osteotomy, the proximal plantar notch that was defined for the Sammarco's modification to increase the contact area was created more proximally making an angle of about 50 degrees with the osteotomy and the osteotomy continued until 5 mm to the distal joint surface. This would increase the contact area and intrinsic stability (Fig. 1e).

A correction table was prepared for the samples enabling a standard correction of 10 degrees. Following correction, the osteotomies were fixed with two interfragmental Acutrak screws 16 mm and 22 mm in size (Acumed, Beaverton, OR, USA). Correction was performed with rotation of the distal fragment about the proximal screw in three osteotomies (Ludloff, offset V, and our modification of Mau) and about the distal screw in the Mau osteotomy, and with translation in the scarf osteotomy. Interfragmental screws were placed at least 1 cm away from each other and from the osteotomy endings (Fig. 1).

After correction and fixation, the samples were subjected to three-point bending test at a rate of 100 mm/min on a Schimadzu Autograph AG-5kNG universal test machine (Schimadzu Corp, Tokyo, Japan). Physiologic loading conditions were simulated where outer points corresponded to the metatarsal joint, and the middle point to the proximal fragment. Bone fracture or implant failure were accepted as failure (Fig. 2). During testing, data on displacement, loading, and stiffness were displayed and recorded by a computer connected to the interface of the test machine. Stiffness was defined as the ratio of 100 N load to displacement (N/mm). Longitudinal loading was not be performed due to inappropriate test material.

Data were analyzed using the SPSS 11.0.1 (for Windows) statistical package program. Data on maxi-

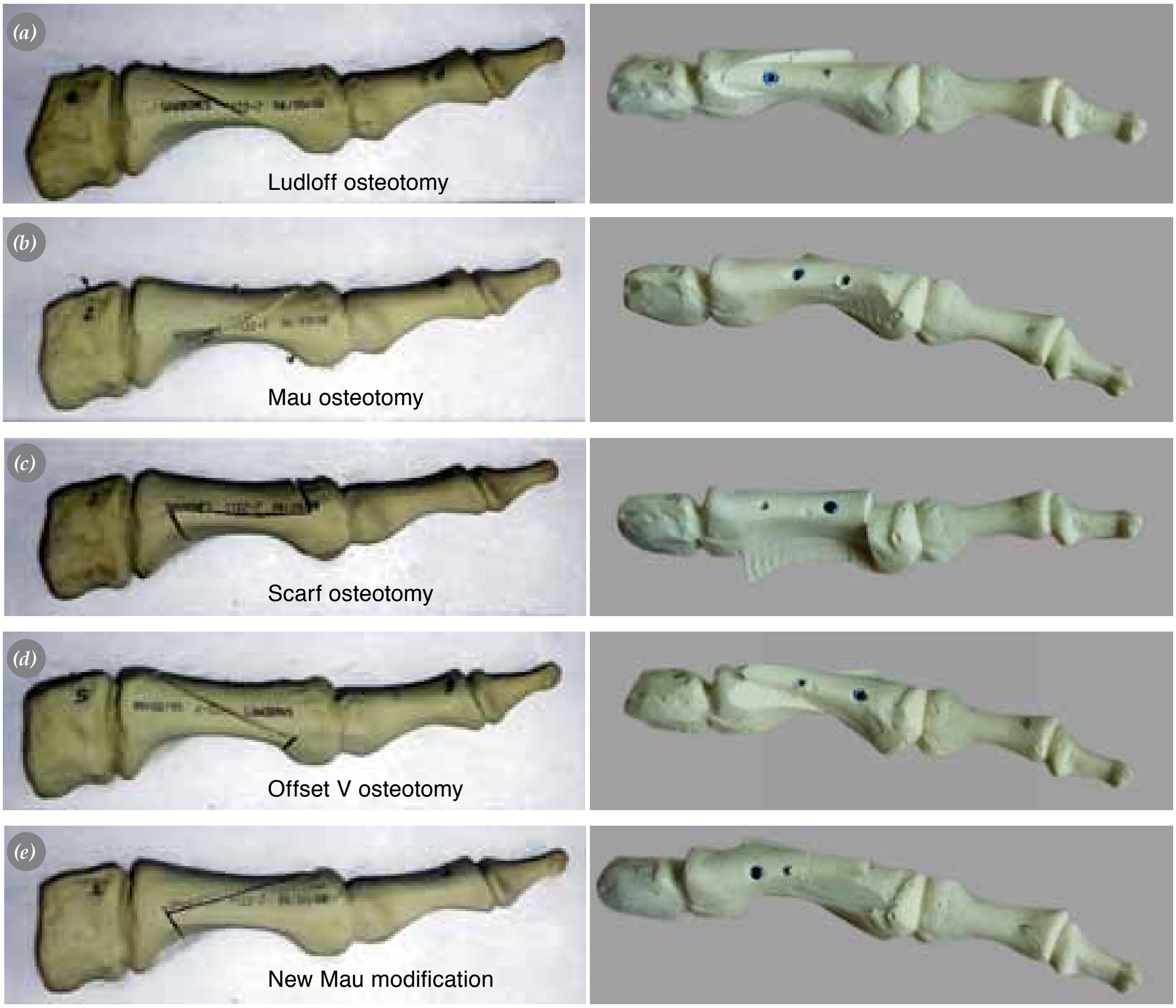

Fig. 1. Metatarsal bone models and the osteotomy methods performed.

mum load to failure, displacement at maximum load, and stiffness were compared between the five groups with the nonparametric Mann-Whitney U-test. Each parameter was also compared between the osteotomy groups with and without notching.

Fig. 2. Assembly of the three-point bending test and failure of the new modification of the Mau osteotomy.

Results

The mean values of maximum load, displacement at maximum load, and stiffness measured in five groups are shown in Table 1. Comparisons between the osteotomy groups with (Scarf, offset V, new Mau modification) and without (Ludloff, Mau) notching and between those with single (Offset V, new Mau modification) and double (Scarf) notching are shown in Table 2.

The mean stiffness of the Ludloff osteotomy was significantly lower than all the other groups ($p<0.05$). Stiffness of the Mau group was significantly greater than other groups except for the offset V group ($p<0.05$).

Table 1

Maximum load to failure, displacement at maximum load, and stiffness measured in five groups

	Maximum load (N) (Mean±SD)	Displacement (mm) (Mean±SD)	Stiffness (N/mm) (Mean±SD)
Offset V	184.1±66.1	5.9±1.1	50.9±24.4
New Mau modification	167.4±37.8	7.3±2.6	41.5±14.0
Ludloff	120.6±47.1	5.9±1.7	21.0±6.2
Mau	248.2±37.5	7.5±3.7	58.0±13.7
Scarf	198.3±48.7	9.9±3.6	28.1±4.1

Stiffness of the new Mau modification was significantly greater than the scarf group, but did not differ significantly from that in the offset V group (Table 3).

Osteotomy groups with and without notching had similar stiffness values ($p=0.582$), whereas single notching was associated with a significantly greater stiffness compared to double notching ($p=0.031$).

Discussion

Distal metatarsal osteotomies have been recommended in mild and moderate hallux valgus, and proximal metatarsal osteotomies in severe cases.[8,18] Pinney et al.[19] performed metatarsal osteotomies in 54 of 102 patients with advanced hallux valgus, which included the Ludloff, proximal crescentic, proximal chevron, scarf, and distal chevron osteotomies. In a series of 64 patients undergoing surgery for hallux valgus in our clinic, we performed a modified McBride procedure in 25 patients, Keller resection arthroplasty in 23 patients, and metatarsal osteotomies in 16 patients.

Concerning the results of the Mau, Ludloff, scarf, and offset V osteotomies, favorable results[8,11,18,20-23] have been reported as well as complications.[14,17,24-27] It is well-recognized that shaft osteotomies require appropriate techniques and a wide range of surgical interventions.

In a cadaver study conducted by Trnka et al.[20] the scarf, Ludloff, and Mau osteotomies were found to be significantly more stable than the chevron and proximal crescentic osteotomies and, among all, the most stable osteotomy was the Mau osteotomy. The authors concluded that the Ludloff and scarf osteotomies allowed greater loads compared to proximal crescentic and proximal chevron osteotomies.

In a biomechanical study with Sawbones models, Acevedo et al.[28] found no difference in stability between the chevron and Ludloff osteotomies, and the proximal chevron osteotomy was found to be more stable than the proximal crescentic and scarf osteotomies. Another study reported greater stability in favor of the Mau, Ludloff, scarf, and biplanar closing wedge osteotomies compared to the proximal crescentic and proximal chevron osteotomies.[20]

Nyska et al.[29] found greater stability with the Ludloff osteotomy compared to the proximal crescentic and proximal chevron osteotomies and reported that the modified Ludloff osteotomy was associated with minimal metatarsal shortening. In another

Table 2

Maximum load to failure, displacement, and stiffness measured in osteotomy groups with and without notching

	Maximum load (N) (Mean±SD)	Displacement (mm) (Mean±SD)	Stiffness (N/mm) (Mean±SD)
With notching (Scarf, offset V, new Mau modification)	183.2±50.7	7.7±3.0	40.1±18.2
Single notching (offset V, new Mau modification)	175.7±52.1	6.6±2.0	46.2±19.6
Duble notching (Scarf)	198.3±48.7	9.9±3.6	28.1±4.1
Without notching (Linear) (Ludloff, Mau)	184.4±78.0	6.7±2.8	39.5±21.8

Table 3
Comparison of stiffness between the five groups
(figures represent p values)

	Ludloff	Mau	Scarf	Offset V
Ludloff				
Mau	0.004			
Scarf	0.037	0.004		
Offset V	0.010	0.749	0.199	
New Mau	0.006	0.037	0.016	0.631

study, it was suggested that the Ludloff osteotomy be performed with a modification of 10 degrees of plantar tilt to prevent metatarsal elevation.[30]

Nyska et al.[31] stated that the Ludloff osteotomy allowed a greater degree of correction than that of the Mau osteotomy and suggested that was related to the rotation center.

In our study, when the stiffness values of the osteotomy groups were compared, it was seen that the Ludloff group had significantly lower values than the other groups. This was attributed to the lower intrinsic stability provided by the geometry of the Ludloff osteotomy. In contrast, the highest stiffness values were seen with the Mau osteotomy which has a higher intrinsic stability. On the other hand, the stiffness values of the offset V and new Mau modification osteotomies having a single notch were found to be significantly higher than the scarf osteotomy with a double notch. This was probably due to the oblique placement of the screws after translation of the scarf osteotomy, resulting in a less stable fixation. Our finding of lower stiffness values with notched osteotomies compared to those reported in other studies may be related with the fact that the stabilizing effect of the notches is more prominent in the longitudinal direction.

There are several issues of consideration for the appropriate application of the screws. Firstly, the screws should be applied perpendicular to the osteotomy line and, to reduce the risk for stress fractures, should not be placed too close to each other. The two ends of the osteotomy line where there is insufficient bone stock present contraindications for screw placement. Distraction of osteotomy or compression loss in the osteotomy line may occur if screws are placed in these regions.[11] In case that two-screw fixation is not feasible, fixation can be completed with a screw and a K-wire. However, in a comparison between screw and K-wire fixation, it has been emphasized that the use of screws would provide a rigid fixation and primary bone healing, whereas K-wire fixation might result in movements in the osteotomy line, secondary bone healing, and prolonged postoperative edema.[11] In our study, for standardization, we used two screws in all the samples.

It has been reported that the proximal screw might cause fractures due to insufficient bone stock in two-screw fixations.[11] In our new modification, the L-shaped osteotomy line leaves a greater amount of bone stock at the ends and enables placement of the screw at a more proximal localization, thus providing a greater angle of correction.

In our study, we used two headless Acutrak compression screws, which is known as the best fixation method, and assessed the consistency of the osteotomy methods with screw fixation and contribution to stability rather than comparing the types of osteosynthesis. The localization of failure was in the distal screw region in the Ludloff and new Mau modification osteotomies, proximal screw region in the Mau osteotomy, and between the two screws in the scarf osteotomy. Separation from the distal screw was noted in the offset V osteotomy. In related studies, failure was reported to occur in the proximal screw region in the Ludloff and offset V osteotomies.[11,13,20,22] In our study, the samples of the Ludloff osteotomy broke from the distal screw region, and separation from the distal screw occurred in the offset V osteotomy. This discrepancy may be due to the differences in the application point of loading during the measurements.

Our study has some limitations due to the use of synthetic bones. Since synthetic bones do not have a medullary channel, some complications of the osteotomies such as channel formation could not be evaluated. On the other hand, due to the lack of proximal and distal joint structures on synthetic bones, longitudinal loading test could not be performed and the stability of the osteotomies, in particular the contribution of notched osteotomies, could not be evaluated in this respect.

Our biomechanical findings suggest that our new modification of the Mau osteotomy offers sufficient stability. Clinical applications may provide more in-formation on the feasibility of the technique, angular correction, early mobilization, early healing and pain relief.

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