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Comparative Mechanical Testing of Different Geometric Designs of Distal First Metatarsal Osteotomies

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ABSTRACT

Background: **The mechanical behavior of a newly described distal metatarsal osteotomy design in the shape of a reversed "L" was compared with the modified chevron and scarf osteotomies.** ***Methods:*** **Experiments were performed using full-sized Sawbone models (Sawbones Europe AB, Malmö, Sweden) of the first ray. Three groups consisting of 10 scarf, 10 modified chevron, and 10 reversed L osteotomies were investigated. All distal fragments were displaced 5 mm laterally without angulation. The proximal fragment of each specimen was embedded in an epoxy resin cylinder and positioned at 15 degrees inclination to the ground. The distal fragment was loaded by a dorsally directed vertical force which was applied at the sesamoid location under the metatarsal head. Load and displacement at failure, work to failure, site of failure and contact areas were recorded for each osteotomy.** ***Results:*** **Similar testing results were obtained in the reversed "L" and chevron osteotomies, while the scarf osteotomy needed almost 5 times less work to failure. In nine of 10 reversed "L" osteotomies and in all scarf osteotomies, the site of failure was at the proximal screw insertion site. The contact areas averaged 163 mm^2 for the reversed "L," 116 mm^2 for the chevron, and 270 mm^2 for the scarf osteotomy.** ***Conclusions:*** **The reversed L osteotomy is a promising design combining the advantages of both the chevron and scarf osteotomies. Further investigations need to be performed to confirm its clinical utility.**

Key Words: Investigation; Mechanical; Metatarsal; Osteotomy

INTRODUCTION

The operative treatment of hallux valgus deformity is intended to provide pain relief and stable restoration of physiological metatarsophalangeal and 1–2 intermetatarsal angles. Among the different operative methods described for treatment of hallux valgus, the scarf and the modified chevron osteotomies have become popular. The diaphyseal scarf osteotomy was first introduced by Zygmunt et al.[34] and then modified by Barouk et al.[4] and Weil et al.[33] The advantage of this operative technique lies in its ability to correct moderate to severe hallux valgus deformities.[5,7,9,18,21,23] Despite reported good results,[9,11] complications such as fractures of the first metatarsal and instability of the osteotomy fragments (troughing) have been reported.[4,8,21,33,34] In contrast, distal metaphyseal osteotomies such as the chevron osteotomy can only be used to correct mild to moderate deformities, allowing a maximal displacement of the head fragment up to 5 mm.[3,12]

In an attempt to avoid these disadvantages, we developed a new technique for distal first metatarsal osteotomy. Because of the L-shaped cut, this osteotomy was named *the reversed "L"* osteotomy. The purpose of this study was to compare the mechanical behavior of the reversed "L" osteotomy with the scarf and modified chevron osteotomies.

MATERIAL AND METHODS

Three groups, each with 10 identical full-size solid foam polyurethane models of the first metatarsal ray (Sawbones Europe AB, Malmö, Sweden), were defined.

Scarf Osteotomy (Figure 1)

A Z-osteotomy was made at the diaphyseal level. The distal and proximal limbs were cut at 45-degree angles through the dorsal and plantar cortex. Next, the plantar fragment was shifted laterally by 5 mm without any angulation and secured with two 2.4-mm cortical lag-screws placed in a dorsal-proximal to plantar-distal direction (10 to 15 degrees of angulation from proximal to distal).

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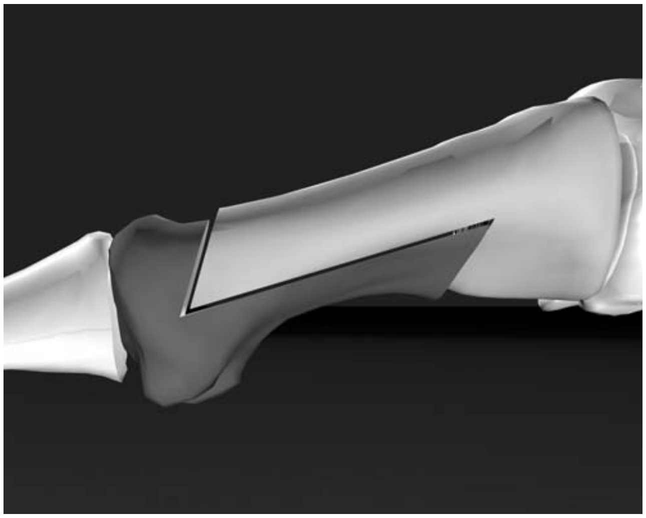

Fig. 1: Scarf osteotomy.

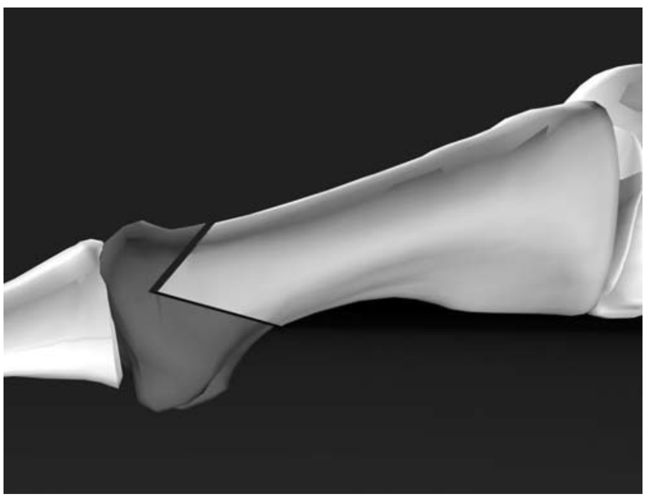

Fig. 2: Modified chevron osteotomy; note the longer plantar arm.

Modified Chevron Osteotomy (Figure 2)[12]

The apex of the osteotomy was centered in the midline of the metatarsal head and positioned 5 mm proximal to the metatarsophalangeal (MP-1) joint line. The osteotomy was made with a long plantar arm and a short dorsal arm (70-degree angle between both arms). The inferior arm was cut parallel to the plantar surface of the foot. The distal fragment was translated laterally 5 mm without angulation and fixed with one 2.4-mm cortical screw inserted in a lag fashion in a dorsal medial to plantar-lateral direction (10 to 15 degrees of proximal to distal angulation).

Reversed "L" Osteotomy (Figure 3)

The apex of the osteotomy was made midway between the dorsal and plantar cortices, 10 mm proximal to the MP-1 joint line. The osteotomy began 10 mm proximal to the MP-1 joint line and extended to the apex, creating the short dorsal arm. The cut then continued with a long plantar arm, perpendicular to the dorsal arm and parallel to the plantar plane. The plantar arm was extended proximally through the plantar cortex of the first metatarsal. The distal head fragment was shifted laterally 5 mm without angulation, and two 2.4-mm cortical screws were placed in a lag fashion with 10 to 15 degrees proximal to distal angulation.

The measured distance of the distal screw insertions to the MP-1 joint line averaged 20 mm (SD $\pm$ 1.4) for the reversed "L" osteotomy, 18.5 mm (SD $\pm$ 1.35) for the chevron osteotomy, and 22 mm (SD $\pm$ 1.4) for the scarf osteotomy. The distance of the proximal screws to the MP-1 joint line averaged 29 mm (SD $\pm$ 1.9) for the reversed "L" osteotomy and 36 mm (SD $\pm$ 1.6) for the scarf osteotomy ($p < 0.0001$). The mean distance of the distal screw to the cut of the distal arm was 7.2 mm (SD $\pm$ 0.8) in the reversed "L" group, 6 mm (SD $\pm$ 1) in the chevron group, and 9 mm (SD $\pm$ 0.8) for the scarf group.

Intact nonosteotomized Sawbones® also were tested to serve as a reference. The proximal part of each Sawbones®

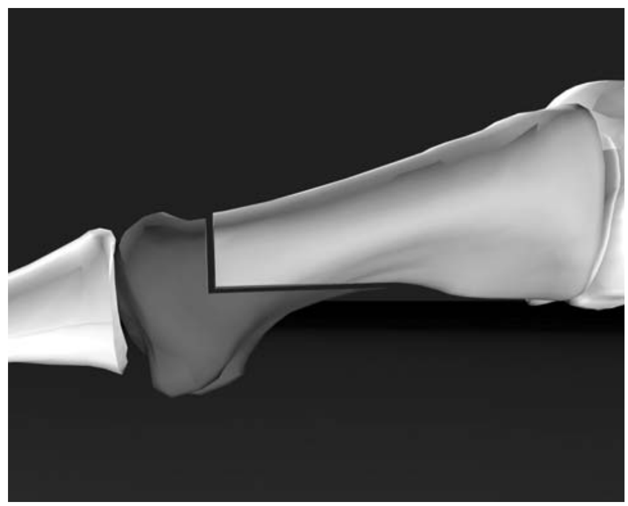

Fig. 3: Geometric design of the reversed-osteotomy.

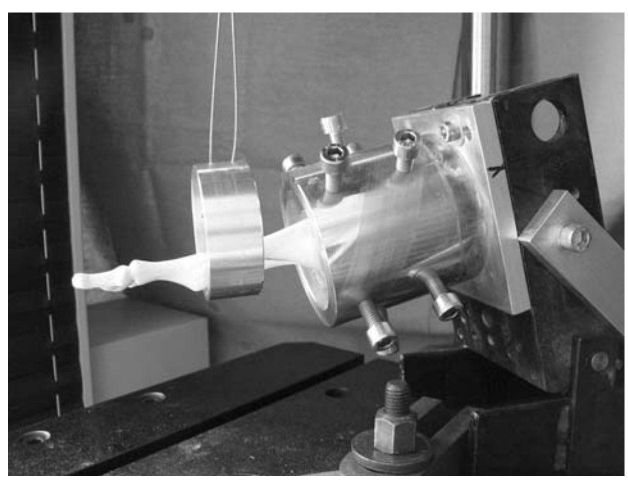

Fig. 4: Fixation of the metatarsal bone for testing.

was embedded in an epoxy resin cylinder (EpoFix, Struers A/S, Ballerup, Denmark) to provide a stable support and to isolate the specimen from the mechanical stresses induced by the gripping device. The specimens were positioned at a 15-degree angle with respect to the ground surface to simulate physiological conditions (Figure 4).[15,16,17,19,31] A vertical load, oriented dorsally, was applied at the location of the sesamoids, underneath the metatarsal head, with an imposed displacement speed of 10 mm/min until gross failure of the specimen (Universal testing instrument model 4204, Instron Corporation, Canton, MA, USA). The load-displacement curves were recorded for each operative procedure and failure was defined as the point at which the maximal load was reached. Work to failure was calculated as the area under the force-displacement curve using the trapezoidal rule.[29] The site of failure was documented for each experiment and the contact area between the fragments was measured by marking the overlapping limb areas and then copying them on transparent foils. The foils were scanned using an EPSON GT 12000 scanner (Seiko Epson, Corporation, Japan) and saved as a PDF-file without changing the image size. Afterwards the images were processed using the Adobe Acrobat 7.0 Professional software (Adobe Systems Inc., San Jose, USA) with the function "measurement tool" to calculate the areas in square millimeters.

Statistical analysis was performed with an ANOVA test using the SPSS software (SPSS Inc., Chicago, IL, USA). The level of significance was set at $p < 0.05$.

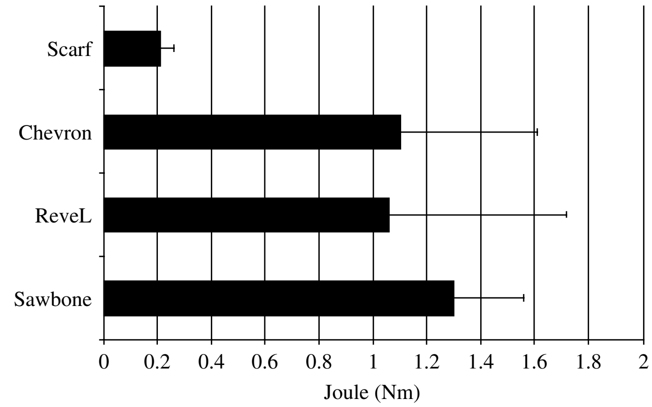

Fig. 5: Work at failure.

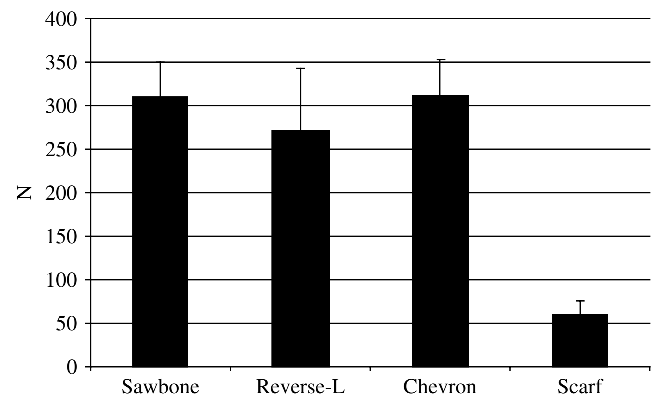

Fig. 6: Load at failure.

RESULTS

The main results are summarized in Table 1. The intact nonosteotomized Sawbones showed an average work to failure of 1.3 J (SD $\pm$ 0.26; Figure 5). The displacement until failure was 8.5 mm (SD $\pm$ 0.9) and the load-at-failure averaged 309.5 N (SD $\pm$ 41; Figure 6). These values served as the reference for calculation of the relative values obtained in the three osteotomy groups.

Table 1: Contact area, relative energy, relative displacement, and relative load to failure for all studied osteotomies and their corresponding statistical significance. All relative values are given in comparison to the nonosteotomized Sawbones model

Parameter	Reference	Scarf	Chevron	Reversed-L	*p*-value
Contact area (mm 2)		270 (±32)	116 (±15)	163 (±20)	scarf-chevron: $p < 0.0001$ scarf-reversed: $p < 0.0001$ chevron-reversed: $p < 0.0001$
Relative energy	100%	16%	85%	82%	scarf-chevron: $p < 0.0001$ scarf-reversed: $p < 0.0001$ chevron-reversed: $p =$ n.s.
Relative displacement	100%	69%	102%	105%	scarf-chevron: $p < 0.0001$ scarf-reversed: $p < 0.0001$ chevron-reversed: $p =$ n.s.
Relative load to failure	100%	19%	100%	87%	scarf-chevron: $p < 0.0001$ scarf-reversed: $p < 0.0001$ chevron-reversed: $p =$ n.s.

The reversed "L" absorbed approximately the same amount of energy (96%) as the chevron osteotomy, but five times more energy than the scarf osteotomy before failure. The relative load and displacement at failure, compared to the nonosteotomized Sawbones, were 19% and 69%, respectively, for the scarf, 100% and 102% for the chevron, and 105% and 87% for the reversed "L" osteotomy. In 9 of 10 reversed "L" ostetotomies, the site of failure was found at the proximal screw insertion site (approximately 24 mm proximal to MP-1 joint line). The failure distance in relation to the apex of osteotomy in the chevron and scarf osteotomies averaged 31 mm (SD $\pm$ 0.8) and 29 mm (SD $\pm$ 4), respectively. The scarf osteotomies all failed at the proximal screw level (approximately 36 mm proximal to MP-1 joint line).

The contact areas averaged 270 mm^2 for the scarf osteotomy, 116 mm^2 for the chevron osteotomy, and 163 mm^2 for the reversed "L" osteotomy.

DISCUSSION

The purpose of this study was to compare the mechanical stability of a reversed "L" distal first metatarsal osteotomy to two frequently used osteotomies. As noted by Sammarco and Acevedo,[30] the position and shape of a metatarsal osteotomy are directly linked to the ability to resist deforming forces in shear and in the transverse plane. Inherent stability of an osteotomy is defined as the ability of the geometric design to incorporate the direct transfer of deforming forces from the distal fragment into the proximal fragment and may vary with the plane of the resultant force vector.[28] In contrast, inherently unstable osteotomies provide little resistance to deforming forces and depend mostly on internal fixation. Inherently stable osteotomies in the sagittal plane include the chevron and the scarf osteotomies.[30]

It is known from the Euler-Bernoulli beam theory that for a cantilever beam (a beam supported only at one end with the other end free to move) with a constant cross-section and loaded perpendicularly on its free end, the induced shear force in the beam is constant in the whole specimen. The bending moment, however, increases linearly from the free to the fixed ends. Those two effects add up to give the internal load pattern within the beam. The fixed end is, therefore, the most vulnerable part of the beam. In our study, the metatarsal Sawbones did not have a constant cross-sectional area. For this reason, the fracture of the nonosteotomized Sawbones did not occur at the fixed end but several millimeters distally. This point is where the mechanical stress (ratio of force over cross-section) is the highest. The geometrical changes resulting from an osteotomy have an influence on the mechanical properties of an osteotomized bone. Analysis of these changes gives insight into the causes of failure and the important parameters influencing mechanical integrity.

Every Sawbone with a modified chevron osteotomy systematically fractured in the same fashion (load at failure, fracture site) as the nonosteotomized Sawbones model, indicating that this type of geometry does not substantially impair mechanical integrity. This type of osteotomy has the most distal apex of the three described operative techniques, ensuring a minimal bending moment at the site of the osteotomy. A drawback of the modified chevron technique is that the single screw and the geometry of the fragments offer little resistance to rotation around the screw axis in the medial lateral plane.[30] This was not observed in the reversed "L" and the scarf osteotomy because they were stabilized with an additional second screw. This second screw, however, revealed a significant problem. In nine of 10 Sawbones models that had reversed-L osteotomies, failure occurred at the proximal screw level, and the remaining specimen fractured 2 mm proximal to that level. Because the bending moment increases in the proximal direction and the proximal screw acts as a stress riser, the site around the screw is prone to fracture.[1,14,27,30] Although the geometric designs of the modified chevron and reversed-L osteotomies resisted comparable average loads at failure in the sagittal plane, the standard deviation of the latter was greater, indicating a reduced degree of reproducibility in the mechanical behavior of the reversed L osteotomy technique. The scarf osteotomy had by far the lowest mechanical resistance of all three operative techniques and required five times less force to fracture than the other two osteotomies. Interestingly, the scarf osteotomy fractured at a displacement of 69% but with a load of only 19% relative to the nonosteotomized Sawbones. Failure always occurred at the proximal osteotomy site where the bone was weakened by the osteotomy which, together with the fixation screws and their drill holes, acted as local stress risers with a comparatively long distal lever arm. This combination may explain the reduced mechanical performance. Fractures of the metatarsals in patients with a classic scarf osteotomy have been described.[4,33,34] Failure was caused by the disruption of the dorsal arm of the proximal fragment, apparently starting at the apex which acts as a stress riser at the proximal corner of the osteotomy.[2] This was confirmed in our study.

The contact area of the reversed-L-shape osteotomy was significantly greater than that of the chevron osteotomy. The contact area is proportional to the corrective potential and healing of an osteotomy as seen, for example, in the design of the scarf osteotomy.[3,6,30]

The main limitation of the study was the use of Sawbones models instead of cadaver specimens. Sawbones do not simulate the viscoelastic properties of bone,[2,10,13,22,24–26] and Landsman and Cheng[24] stated that the mechanical strength of cadaver bone is superior to the Sawbones model. For this reason, absolute values obtained with Sawbones certainly do not correspond to those measured in fresh-frozen metatarsals. However, previous studies,[13,20,22,24,26] suggested a sufficient reliability of Sawbones for comparison of relative stability, even though absolute values were not clinically relevant. Our goal was to compare the mechanical behavior of different geometric assemblies, so we showed only relative values from the mechanical testing, all related to the values measured on the nonosteotomized metatarsal Sawbones model. The use of Sawbones models also excluded possible influencing factors, such as tissue quality and bone size, shape, and architecture,[24,32] and isolated the effect of the geometrical parameter. Another limitation is that the external force was applied at a specific point in our experiments, whereas in vivo the ground reaction force is distributed by the soft tissues.

Despite these limitations, the reversed-L osteotomy may be of value for correcting severe hallux valgus by combining the advantages of both the scarf (ability to correct large deformities due to the large contact area) and the modified chevron osteotomy (mechanical resistance).

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