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ABSTRACT

Background
Among the numerous osteotomies for correction of Hallux Valgus, the modified chevron is known for its good intrinsic stability and the scarf for its large corrective potential. An intermediate design, the reversed-L osteotomy, has been developed to combine these competing biomechanical objectives. The purpose of this in vitro study was to compare the structural and local biomechanical performance of these three designs.

Methods
Stiffness, cortical bone strains (a factor relevant to bone remodeling), strength and failure mode of the scarf, modified chevron and reversed-L osteotomies were measured on human specimens in two different loading configurations.

Findings
The scarf osteotomy caused significant changes in stiffness and cortical bone strains with the proximal apex being at the origin of bone failure. The chevron and reversed-L had a generally comparable response to the intact bone. The chevron specimens failed by pivoting of the distal fragment, and the reversed-L by pivoting or fracture.

Interpretation
This is the first study to investigate the cortical bone strain changes induced by these invasive osteotomies. Alterations from the intact bone response could be directly related to the design of the osteotomy. Notably, the critical weakening proximal apex of the scarf is avoided in the reversed-L, leading to results comparable to the chevron. This study provides support in favor of the intermediate design of the reversed-L as an effective compromise between the competing biomechanical objectives of corrective potential and mechanical stability.

Keywords: Hallux valgus, osteotomy, Scarf, chevron, reversed-L, failure, strain distribution, first metatarsal.
INTRODUCTION

Hallux valgus is characterized by a lateral deviation of the hallux accompanied with a medial displacement of the distal end of the first metatarsal (MT1). This very common foot deformity has been reported to affect 2 to 4% of the population (Myerson, 1999). For moderate to severe hallux valgus, first metatarsal osteotomies are often performed to restore first ray alignment (Robinson, 2005). The modified chevron osteotomy has been shown to lead to very good clinical outcome and is generally considered to provide superior intrinsic mechanical stability (Sammarco, 1993, Donnelly, 1994). However, excessive correction could lead to instability, delayed union, malunion or avascular necrosis (Badwey, 1997, Donnelly, 1994, Murawski, 2008). On the other hand, the scarf osteotomy (Barouk, 2000, Weil, 2000, Zygmunt, 1989) is widely employed as it allows correction of moderate to severe hallux valgus. Although the clinical results are generally satisfactory (Lorei, 2006, Dereymaeker, 2000, Barouk, 2000, Crevoisier, 2001, Aminian, 2006, Lipscombe et al., 2008), several complications of mechanical nature have been reported, notably fracture or troughing (Barouk, 2000, Jones, 2005, Weil, 2000, Zygmunt, 1989), with rates reaching 10% and 35% respectively (Coetzee, 2003). In an attempt to combine the intrinsic mechanical stability of the chevron with the corrective potential of the scarf, an intermediate design, the reversed-L osteotomy, has recently been developed at our institution (Espinosa, 2006, Helmy, 2009). The corrective potential being directly related to the available contact surface (Badwey, 1997, Sammarco, 2001, Borton and Stephens, 1994), the reversed-L has proven to allow significantly more correction than the chevron osteotomy (Vienne, 2007).

Understanding the biomechanical consequences involved in such an invasive procedure is of prime importance to reduce the rate of complications and improve the treatment. For various types of osteotomies, initial stability has been tested experimentally by measuring the ultimate strength and stiffness on human bones (Trnka et al., 2000, Miller, 1994, Shereff, 1991), or on
polyurethane MT1 models (Acevedo, 2002, Shaw, 2001, Jacobson et al., 2003, Gonda et al., 2002, Vienne, 2007). This is clinically important, since an osteotomy design characterized by better initial stability allows earlier postoperative weightbearing (Easley, 2007). One of these studies brought first insights in the comparative mechanical response of the scarf, chevron and reversed-L osteotomies (Vienne, 2007). However, it focused exclusively on parameters related to failure and was performed on Sawbones, with all the limitations associated with these models. To date, no study has assessed the manner in which the intact MT1 deforms, and how deformation is affected by different osteotomies. However, cortical bone strain patterns are important when one aims at restoring the mechanical loading found in the intact bone to avoid later complications. Any changes from a “natural” bone loading pattern may have two consequences. First, following Wolff’s law (Wolff, 1892), the bone would remodel to best sustain the new mechanical state, which, in the long term, could lead to modifications of the gross bone anatomy (Goodship, 1979). A second concern is that the altered mechanics may transfer to the adjacent bones, tissues and joints, leading to further complications.

The purpose of this in vitro study is to investigate the biomechanics of two established and one new osteotomy designs, by assessing their global mechanical behavior (stiffness and failure) and local cortical bone strains on human specimens. Intact MT1 specimens are measured as a baseline for comparison of the scarf, modified chevron and reversed-L osteotomies in two different loading configurations. First, this should provide a better understanding of the biomechanical consequences of two of the most popular MT1 osteotomies (chevron and scarf). Second, it should allow assessing the performance of the new reversed-L procedure and evaluate its biomechanical potential. This information is central to improve the management of surgical treatment of hallux valgus.
METHODS

Specimens

Fifteen fresh-frozen human cadaveric MT1 were harvested from 10 cadavers with a mean age at death of 75.1 years (range, 56 to 88). The feet were verified to be free of foot pathologies. All soft tissues were removed and the specimens were conserved between experiments by wrapping in saline soaked cloth and stored at -20°C. The average length of the metatarsals was 6.83 cm (range, 6.2 to 7.2 cm).

Strain measurement

General purpose rosette strain gages were used (type CEA-06-062ww-120, Vishay Intertechnology Inc., Malvern, PA, USA) for in vitro cortical bone strain measurement (Figure 1). In a pilot study, three uniaxial gages were glued circumferentially in the longitudinal direction on the mid-diaphysis with cyanoacrylate adhesive: one each on the dorso-lateral, medial and plantar-lateral aspects of the MT1. In both loading configurations (see below), the bone bent dorsally and the dorso-lateral aspect was the most strained. Therefore, the dorso-lateral aspect had the advantage of consistently measuring the largest bone strain magnitudes, and facilitated direct comparison between the various osteotomies for the considered loading modes, after normalization. The methods of normalization are described later in section Data analysis. Moreover, the chosen location facilitated ease of sensor mounting, as well as the measurement of the strains not too close to the cuts to be performed later. The strains were digitized and stored using Labview v8.5 (National Instruments, Austin, TX, USA).

Loading

The proximal end of each specimen was embedded in an epoxy resin cylinder (EpoFix, Struers A/S, Ballerup, Denmark) to enable reliable fixation to the testing machine and to isolate the specimen from the deformations induced by the clamping apparatus. Each potted
specimen was fastened on two linear tables (SFERAX SA, Cortaillod, Switzerland) mounted perpendicularly, to allow the specimen to translate freely in the plane of the ground, thus reducing application of off-axis forces from the applied loading.

All bones were tested in two different loading configurations, cantilever and physiological (Figure 2). In the cantilever configuration, the specimens were positioned with an angle of 15° between the axis of the first ray and the ground surface. A vertical load, oriented from plantar to dorsal was applied to the metatarsal specimen. This arrangement represents the most frequently used testing configuration (Vienne, 2007, Trnka, 2000, Jones et al., 2005, Sharma et al., 2005). It simulates the anatomic position of the MT1 when the subject is standing, simulating the effect of the ground reaction force only. The cantilever configuration does not consider the effect of muscular contraction during locomotion, which is substantial and was, for the first time, accounted for in the physiological configuration. The sum of the ground reaction and muscular forces acting at the metatarsophalangeal joint was previously estimated when the forefoot is most heavily loaded, i.e. at push-off (Jacob, 2001). This force makes a 13° angle with the longitudinal axis of the MT1.

The load was applied to the distal fragment through the condyles with a universal uniaxial testing machine (Zwick 1456, Zwick Inc. Ulm, Germany) at a displacement rate of 2mm/min. The maximum applied load was kept sufficiently low to avoid damage to the specimens, with 550N applied in the physiological configuration and 150N in the cantilever configuration. The load-displacement curves were recorded for each trial simultaneously with the strain gage data.

After non-destructive testing, all intact bone specimens were randomly attributed to one of three different osteotomy groups: scarf, modified chevron and reversed-L osteotomies.
**Osteotomies**

In all procedures, the distal fragment was translated laterally 5mm without angulation and secured with 2.4mm cortical lag-screws placed in a dorso-proximal to plantar-distal direction (10-15° angulation from proximal to distal). Five specimens were arbitrarily attributed to each osteotomy type.

For the scarf osteotomy (Figure 3), a Z-osteotomy was performed at the diaphyseal level, extending proximally towards the first tarsometatarsal joint but with a minimal distance to the latter of 10-15mm. The distal and proximal limbs were cut at 45-60° angles through the dorsal and plantar cortex. Two screws were used for fixation.

For the modified chevron osteotomy (Donnelly, 1994), the apex of the osteotomy was centered in the midline of the metatarsal head and positioned 10 mm proximally from the metatarso-phalangeal joint line. An angle of 70° was achieved between the two arms and oriented such that the longitudinal axis of the bone was coincident with the angle bisector. One screw was used for fixation.

For the reversed-L osteotomy, the apex of the osteotomy was localized midway between the dorsal and plantar cortices, 10 mm proximal to the metatarso-phalangeal joint line. The long plantar arm was cut parallel to the plantar plane of the foot and a short dorsal arm perpendicular to the latter. The fragments were secured with two screws.

All bones were then re-tested in both loading configurations, using the protocol described for the intact MT1. In a final step, the force-displacement curves of all specimens were measured when loading them to failure in the cantilever configuration, with the strength defined as the maximal force. The fracture mode was observed by simultaneously recording a movie of the specimen using high speed video cameras (Basler A622F, Basler Vision Technologies AG, Ahrensburg, Germany).

**Data analysis**

The force-displacement and strain gage-displacement data were analyzed in Microsoft Excel.
For calculation of the stiffness, a linear regression was fitted to the force displacement curve ($R^2$ average value was 0.995, with a range from 0.956 to 0.999) and its slope taken as the stiffness.

The three strain measurements obtained by the rosette gages were used to calculate the maximal principal strains (Vishay Micro-Measurements Tech Note TN-515). In order to allow a numerical comparison between the different osteotomies, the strains measured at a load of 50N were extracted. The 50N load was chosen because the strain data were in the linear range up to this force for all tested cases.

In order to allow a comparison between bones from different subjects, biases from interindividual anatomical variation must be considered. The stiffness and maximal principal strain data were normalized by calculating the ratio of each osteotomized bone to its value in the intact state.

Statistical analysis was performed with the non-parametric Mann-Whitney test. The level of significance was set to $P<0.05$.

**RESULTS**

In cantilever loading (Figure 4), the scarf and the chevron osteotomies induced a statistically significant ($P<0.01$) drop in stiffness when compared to the intact bones, while the bones operated with the reversed-L showed a more variable stiffness. The scarf osteotomy led to bone strains significantly higher than the intact bone ($P<0.01$) and higher than both other osteotomies ($P<0.01$). No statistical difference was detected for differences in failure load.

In physiological loading (Figure 5), the specimens operated with the scarf and the reversed-L osteotomies had a statistically significant ($P<0.01$) decrease in stiffness when compared to the intact bones. No statistical difference was detected in the surface strains when loaded in the physiological configuration, but the scarf osteotomy led to highly variable bone strains.
When tested to failure, all five scarf specimens fractured at the proximal segment, at the height of the proximal apex of the cut, with a crack propagating at an approximative 45° angle with respect to the longitudinal axis of the bone (Figure 6). All five chevron specimens failed as a result of rotation of the distal segment about the apex of the proximal segment. For the reversed-L osteotomy, three specimen failed by rotation of the distal segment, two failed by fracture of the proximal segment near the proximal screw.

**DISCUSSION**

In this experimental study, biomechanical measures of structural bone properties and local cortical bone strains were quantitatively compared for intact and osteotomized human MT1 bones in two different loading conditions. Alterations from the intact bone response were directly dependent on the design of the osteotomy. All osteotomies involve large geometric alterations, displacing the locus of force application and changing the stress pattern within the bone. This in turn influences the way the bone deforms, and consequently how the cells in the bone might later respond to the resulting in vivo loads (Isaksson, 2006). In order to estimate this effect, as might be expected shortly postoperatively, we measured local cortical strains. Furthermore, during the postoperative rehabilitation period, any secondary displacement of fragments or instability could impair proper healing or outcome (Robinson, 2005). In order to assess primary stability, bone stiffness, strength and failure mode were quantified.

*Scarf osteotomy*

Of the three tested osteotomy types, the scarf osteotomy created the most considerable changes, which can be directly linked to the design of the scarf osteotomy. First, with the longitudinal arm of the osteotomy positioned more dorsally, less bone is available on the proximal segment for load bearing. The force is transferred through only a small remaining portion of the cross-section (Vienne, 2007). This part is therefore more deformed, leading to the higher measured local strains on the dorsal aspect. This, combined with the stress raiser
effect of the osteotomy corner, make this location particularly vulnerable to fracture. This is in accordance with a previous in vitro study, where all bones operated with the scarf failed by fracture of the proximal dorsal bridge (Popoff, 2003). Using high speed video, we could identify that this failure originated at the proximal apex. This is further corroborated by clinical results, where fractures have been reported to occur at the proximal aspect of the bone, accounting for 10% of the complications (Coetzee, 2003). Second, other than in the chevron and reversed-L osteotomies, no failure mode in rotation of the distal fragment was observed. This indicates that a stiff primary fixation could be achieved between the two fragments of the scarf. In contrast to the chevron, no energy was dissipated in rotation of the distal fragment. The load could be effectively transferred to the proximal part, deforming the latter to a larger extent.

Although not significant, strength was generally lowest for the scarf osteotomy. This is partly in accordance with a previous study that found a significantly lower strength for the scarf (Vienne, 2007). The earlier study was performed on Sawbones, and divergence in the mechanical properties and architecture of these bone surrogates from real bone may have led to these accentuated disparities and differences in statistical significance. Moreover, the longitudinal cut extended less proximally in the present study. Conversely, anatomical variability in the human specimens may have precluded a significant result.

Chevron osteotomy

The specimen operated with a chevron osteotomy had a significantly lower stiffness than the intact bones when loaded in cantilever. This observation may be related to the very consistent failure mode of the chevron; all failed by pivoting of the distal fragment. This rotation started with low forces already (as could be seen on the recorded high speed videos), leading to the significantly lower measured stiffness. In contrast to the scarf, the fragments of the chevron are fixed together by only one screw, positioned very close to the apex of the cut, and thereby probably only able to offer little resistance to pivoting of the distal fragment. For all other
tested parameters, the chevron had a generally comparable behavior to the intact bones, confirming this osteotomy as a biomechanically feasible design (Donnelly, 1994, Sammarco, 2001, Vienne, 2007). In the absence of a proximally extending arm, the chevron osteotomy was not shown to alter the strains at the gage location, probably keeping the strain alterations more distal.

Reversed-L osteotomy

As with the chevron osteotomy, the reversed-L had a generally comparable biomechanical performance to the intact bone. Only the stiffness in physiological loading was significantly different from the stiffness of the intact bone. Advantageous features of the chevron and scarf were combined in the intermediate design of the reversed-L osteotomy. Compared to the scarf, the plantar arm of the reversed-L osteotomy does not have the critical proximal apex, leaving a much greater portion of the proximal MT1 aspect intact, weakening this part of the bone to a lesser degree, and leading to generally better biomechanical results. This allows the reversed-L osteotomy to achieve comparable mechanical properties to the chevron. Compared to the latter, a significantly greater interfragmentary contact surface was measured with the reversed-L osteotomy (Vienne, 2007), allowing for larger corrections to be performed. An intermediate behavior is evident in the failure modes of the reversed-L, which consist in a mix of the typical failure modes of the chevron and scarf. In two specimens, bone fracture occurred. Fracture was located at the height of the proximal screw, indicating that this acted as a stress raiser. In three specimens, distal segment pivoting occurred, as for the chevron. This was certainly possible because contrary to the scarf, the reversed-L uses two screws with a smaller distance apart, making the construct less able to withstand turning moments. Finally, although insignificant, the strength was generally highest for the reversed-L. These good biomechanical results, together with first positive reports of clinical outcome (Helmy, 2009) indicate that the reversed-L could be an effective alternative to the available first metatarsal osteotomies.
This study has several limitations. A loading configuration may favor one type of osteotomy in comparison to others. The two chosen loading conditions may not replicate the most critical situation for the mechanical resistance of the osteotomy. Fractures may occur through trauma, or due to extraordinarily excessive muscle contractions in unusual circumstances, such as in sliding or stumbling. However currently, there is a lack of knowledge on the etiology of fractures of healing MT1 osteotomies. The influence of bone quality has not been addressed, although this is a well documented determinant of bone mechanical behavior (Zioupos, 1998). Although the pilot study on gage location helped us determine the best site out of three, the strain gages only allow monitoring of bone strains in very localized anatomical regions. Since intact bone strains were measured in non-destructive tests the reported strains may not be representative of peak values. This investigation only addresses primary stability, i.e. the immediately postoperative situation. In an attempt to overcome many of these limitations, and to obtain a more complete description of the stress/strain distribution in the whole bone, the overall deformation and influence of correction, a finite element model of different osteotomized MT1 is currently being developed at our institution, with the present study intended to serve as experimental reference.

**CONCLUSIONS**

The scarf osteotomy induced the largest changes in both the local and global biomechanical behavior of the MT1. The proximal apex of the longitudinal cut is critical, and should not be too proximal in a patient at risk for MT1 fracture. The chevron and the reversed-L osteotomies had a generally comparable mechanical response, with minimum alterations from that of the intact bone. The current study provides support in favor of the reversed-L osteotomy as a feasible treatment option, from a mechanical point of view. Its unique intermediate design allows the reversed-L to combine the mechanical stability of the chevron with the larger correction potential of the scarf.
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Vishay Micro-Measurements Tech Note Tn-515: Strain Gage Rosettes: Selection, Application and Data Reduction.


FIGURE LEGENDS

Figure 1: Dorsal and lateral views of first metatarsals operated with the scarf, chevron and reversed-L osteotomies. Note the position of the strain gage at the mid-length of the bone, on the dorso-lateral aspect.

Figure 2: Experimental set up for the cantilever (A) and physiological tests (B) including the estimates of muscle forces. The arrow indicates the direction of the applied load.

Figure 3: Design of the scarf (top), chevron (middle) and reversed-L (bottom) osteotomies.

Figure 4: Stiffness (A), strains (B) and load to failure (C) of the MT1 in cantilever loading. All stiffness and strain values were normalized to the intact bones, which were set to 100 %. The error bars link the most extreme values.

Figure 5: Stiffness (A), strains (B) and load to failure (C) of the MT1 in physiological loading configuration. Positive strain ratio stands for compression, negative strain ratio represents compression. All values were normalized to the intact bones, which were set to 100 %. The error bars link the most extreme values.

Figure 6: Failure mode of the scarf (left), chevron (middle) and reversed-L (right). The upper panel represents the unloaded bones, the lower panel shows the bones at failure. All five scarf specimen fractured at the proximal apex (arrow), all chevron specimens failed by distal segment rotation. Three reversed-L specimen failed by rotation of the distal segment, two by fracture of the proximal segment at the height of the proximal screw (arrow).
**Figure 1:** Dorsal and lateral views of first metatarsals operated with the scarf, chevron and reversed-L osteotomies. Note the position of the strain gage at the mid-length of the bone, on the dorso-lateral aspect.
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