The postoperative stability of the first metatarsal

H. Prosche[1], R.A. Fuhrmann[2], W. Linβ[1] and R. Fröber[1]

1- Institute of Anatomy I

2- Department of Orthopaedics

Faculty of Medicine, Friedrich Schiller University Jena, 07740 Jena, Germany

SUMMARY

The hallux valgus deformity is characterised by an increased first intermetatarsal angle, which can be reduced by osteotomies on the first metatarsal bone, such as the Proximal osteotomy and the Scarf shaft osteotomy. Osteotomy and subsequent screw fixations were performed on 18 matched pairs of cadaveric specimens to compare the postoperative stability of these two common types of operative correction. Biomechanical testing with plantar force was carried out and failure load was measured for each specimen. The results indicate that the threaded bones provide a high postoperative loading capacity. When maximal strain was exceeded, the specimens failed in the proximal third, irrespective of the type of osteotomy. Moreover, we found that in contrast to the living age the mineral density and the individual geometry of the bone have a marked influence on the postoperative loading capacity.

Finally, static biomechanical studies demonstrated that the Scarf osteotomy is significantly more stable than the commonly used Proximal osteotomy. Regarding the early postoperative mobilization of the patients concerned, the Scarf osteotomy proved to be superior, but the Proximal osteotomy requires a more cautious rehabilitation program.

Key words: Hallux valgus – Human metatarsal bones – Osteotomy – Biomechanics – Comparative study

INTRODUCTION

Osteotomies are performed in case of hallux valgus to correct the medial deviation of the first metatarsal. The angle between the first and second metatarsals is often enlarged to more than 15 degrees. During the osteotomy this intermetatarsal angle is reduced by a lateral displacement of the distal fragment. Since the aim is immediate postoperative weight bearing, more detailed information concerning the postoperative stability of the first metatarsal is of great importance. Discrepancies between weight bearing and osseous stability may lead to malunion of the metatarsal shaft followed by elevation of the metatarsal head and transfer metatarsalgia (McCluskey et al., 1994; Trnka et al., 1999). In the context of the study of isolated human first metatarsals, two current methods of osteotomy were analysed concerning their postoperative mechanical stability. Both methods include a proximal osteotomy characterized by a transverse cut perpendicular to the metaphysis of the bone and the Scarf one by a horizontal z-shaped cut through the diaphysis of the bone.

The aim of this study was to determine the primary stability of the metatarsals and to develop criteria facilitating the differential indication for both methods. The influence of biometrical parameters, such as bone diameter and length as well as its microarchitecture, on the mechanical stability was elucidated. A further aim was to evaluate the relevance of bone mineral density as well as that of patient age and sex.

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Correspondence to:
Rosemarie Fröber, MD. Institute of Anatomy I, Friedrich Schiller University, Teichgraben 7, D-07740 Jena, Germany. Phone: +49-3641-938520; Fax: +49-3641-938512
E-mail: rfro@mti.uni-jena.de

Material and Methods

The first metatarsals of 18 adult human cadavers (8 males, 10 females) were tested. Age at death was mostly between 60 and 90 (average 69.5) years. The metatarsals were taken out of the unfixed cadaver a few hours posthumously, isolated from the soft tissues, and kept hermetically sealed at –26 °C. Patients with previous forefoot surgery were excluded from the study.

Densitometric analysis

The bone mineral density of the first metatarsal bones was measured with a peripheral quantitative computer tomograph (pQCT) XCT 900 by STRATEC Pforzheim. The triple measuring focused on the proximal metaphysis and the diaphysis of the bone because these regions were used for the methods tested. To ensure reproducible measuring conditions, a custom-made fixating device was developed.

First, the metatarsals were scanned in a meander-shaped manner along their longitudinal axis. On the basis of this scan, the final measuring points were defined. They were located in proximal-distally direction at 10%, 15%, 20%, and 30% of the total bone length. Based on these CT scans and a standardised scan thickness of 2.5 mm, the computer created a CT image from the data. Further calculation using a scoring program led to density values in mg/cm^3 and the respective cross sectional area of the CT sections in voxels (1 voxel = 0.59 x 0.59 mm). The results of the quantitative densitometric analysis had been compared with the microarchitecture of the first metatarsals, which we had analyzed in saw cuts through macerated specimens.

Osteotomy

Two common methods of osteotomy were performed on the isolated first metatarsals (Fig. 3). It was done pair-matched and alternating to compensate for right-left differences within individual bone couples. The Scarf osteotomy was performed in a z-shaped manner at the diaphyseal part of the bone. After lateral displacement of the distal fragment, the bone fragments were stabilized with two screws. The Proximal osteotomy was accomplished by a transverse saw cut running perpendicular to the shaft axis about 1 cm distal to the first tarsometatarsal joint. Fixation of the bone fragments was carried out using a 3.5 mm cortical screw.

Loading tests

To test the postoperative stability of the metatarsals, a universal testing unit - type UPG 100 - was used. According to the in vivo situation, the bones were fixed within the testing device at its uppermost proximal base using polymethylmetacrylate. The metatarsal head was charged with a plantar force, moving with a continuous speed of 30 mm/min. This led to a bending stress of the bone until its complete failure. We analysed the extent of resilience as well as the mode of failure after exceeding the maximal strain to both types of osteotomy.

Results

Postoperative stability

Our data revealed highly significant differences between both osteotomies as regards the metatarsal stability. The maximal force that could be exerted to the metatarsals prior to their failure was significantly higher in all bones with Scarf osteotomy as compared to that with Proximal osteotomy. The mean value of force prior to failure was 160.39 N in case of the Scarf osteotomy and 70.89 N in case of Proximal one (Fig. 1). These results indicate that, in Scarf osteotomy the ultimate loading capacity was more than 2 times higher compared to the proximal method.

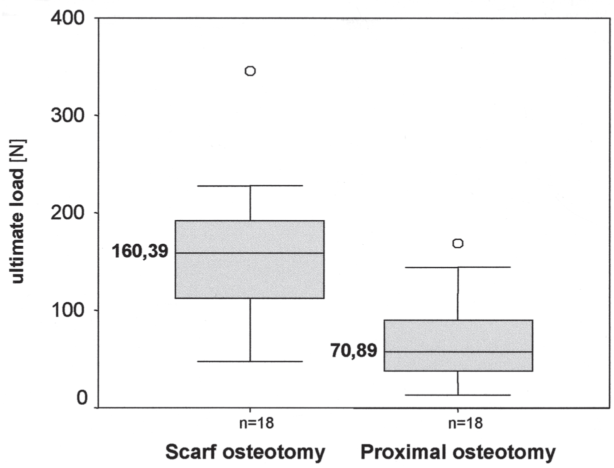

Fig. 1.- The failure load turned out to be higher in case of the Scarf osteotomy than of the Proximal one.

Biomechanical testing

Clearly illustrated by the graph of the loading deformation of a tested bone couple, the mechanical behaviour of the charged metatarsals differs depending on the type of osteotomy (Fig. 2). In the Scarf osteotomy, the rising part of the curve was nearly linear and steeper and the maximum load was twice as high as to the compared method. The abrupt decay of the curve correlates with the failure of the bone. The region of failure was referred to the short proximal cut of the z-shaped osteotomy (Fig. 3). The Proximal osteotomy was characterized by an arched increase of the curve, a comparatively low maximum being reached in all cases. The following decrease in a saw tooth manner corresponded to a gradual slackening of the osteosynthetic screws.

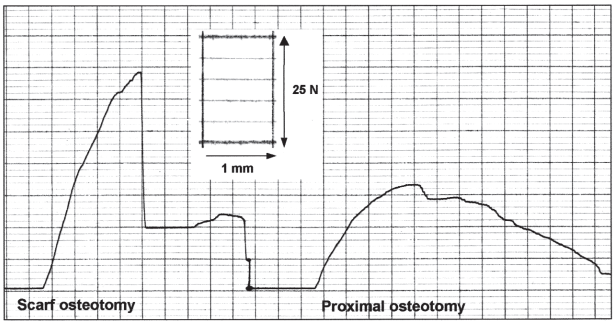

Fig. 2.- Exemplary load deformation curves (→ means 1 mm way of the piston of the testing device). The graph shows a steep rise during the force increase, with an abrupt dropping away after the maximum load in case of the Scarf osteotomy. Concerning the Proximal osteotomy, there is a slower increase and a gradual decrease.

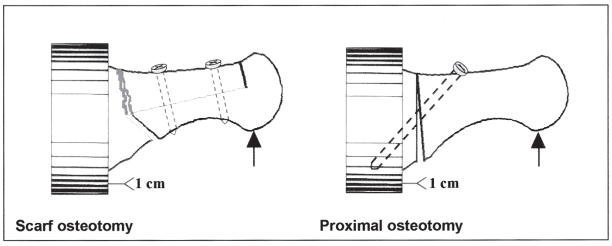

Fig. 3.- All tested bones were embedded with their basal end in polymethylmetacrylate. The metatarsal head was charged with a plantar force (↑), moving with a continuous speed of 30 mm/min. This led to a bending stress of the operated bone and finally to its complete failure.

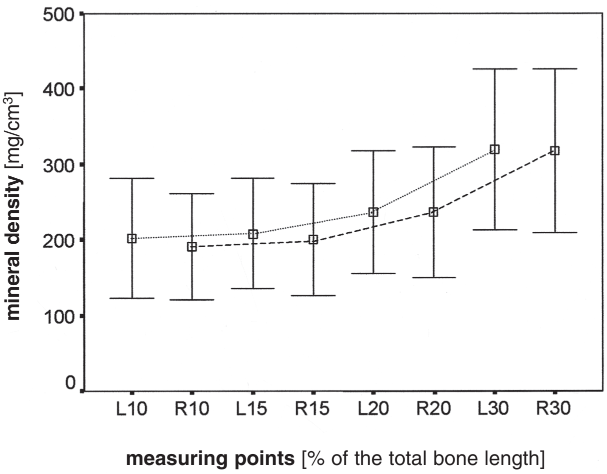

Fig. 4.- The bone mineral density increases in the proximal third (10%, 15% and 20% of the total bone length) of all the considered 18 left [L] and 18 right [R] metatarsal bones. The increase is significant ($p<0.001$) at the level of 30%. The left bones' variables are linked by a dotted, the right ones by a broken line.

Biometric parameters

The loading tests demonstrated that the screw slackening in the case of the Proximal osteotomy as well as the fracture in case of the Scarf osteotomy were both located at the proximal third of the first metatarsal. The structural characteristics of this region were evaluated by mineral density measurements. For all of the 18 bone couples considered the data, shown in Fig. 4, indicate a slight increase in the mineral density in the distal direction (10%, 15% and 20% of the total bone length). At the level of 30%, this increase was significant, with $p<0.001$. Detailed micro-architecture characteristics are presented in a saw cut through a macerated first metatarsal (Fig. 5). As seen in the cut, the trabecular zone within the metaphysis of the bone is formed by a dense network anchored in an acute-angled manner in the sparse cortical zone, especially in dorsal direction. By contrast, within the diaphysis of the bone we found the trabecular zone in a longitudinal orientation, forming a sparsely organised network with numerous cavities, especially in plantar direction. Moreover, the cortical layer was much stronger than that of the metaphysis. This correlates with the above-mentioned significant increase in mineral density at the 30% level of total bone length.

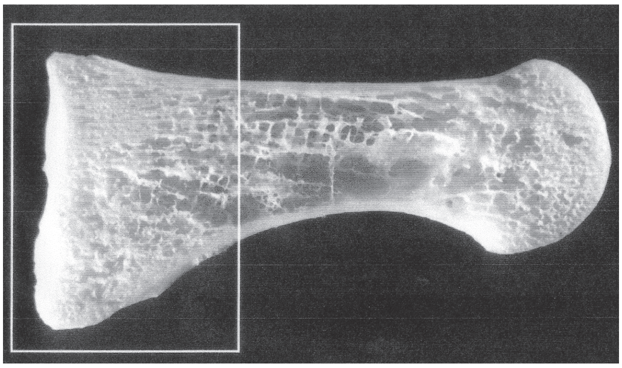

Fig. 5.- Datailed micro-architecture characteristics are presented by a saw cut through a macerated first matatarsal. The area of the bone mineral density measurements is marked.

Variables influencing postoperative stability

In both osteotomies postoperative stability is characterized by considerable individual variations. Nevertheless there was no correlation between stability and age at death. The variations in loading capacity were caused by individual differences both in bone length and deviations in osteotomy sites, resulting in different lever arms during the mechanical tests. To take these factors into account, the bending moment (Nm) of bone was calculated by a multiplication of the equivalent of the lever arm (distance between the point of piston contact and point of failure) and the ultimate load. On the basis of this bending moment, effective postoperative stability could be analysed. The data revealed a significant correlation between this effective postoperative stability and the mean mineral density of the first metatarsal. Moreover, a significant sex-independent correlation to the cross sectional area of the bone at the point of failure (about 1 cm distal to the tarsometatarsal joint) was found. Thus, it can be affirmed that the mineral density and the individual biometric parameters, such as the length and the diameter of the bone, have a marked influence on the postoperative loading capacity (Fig. 6).

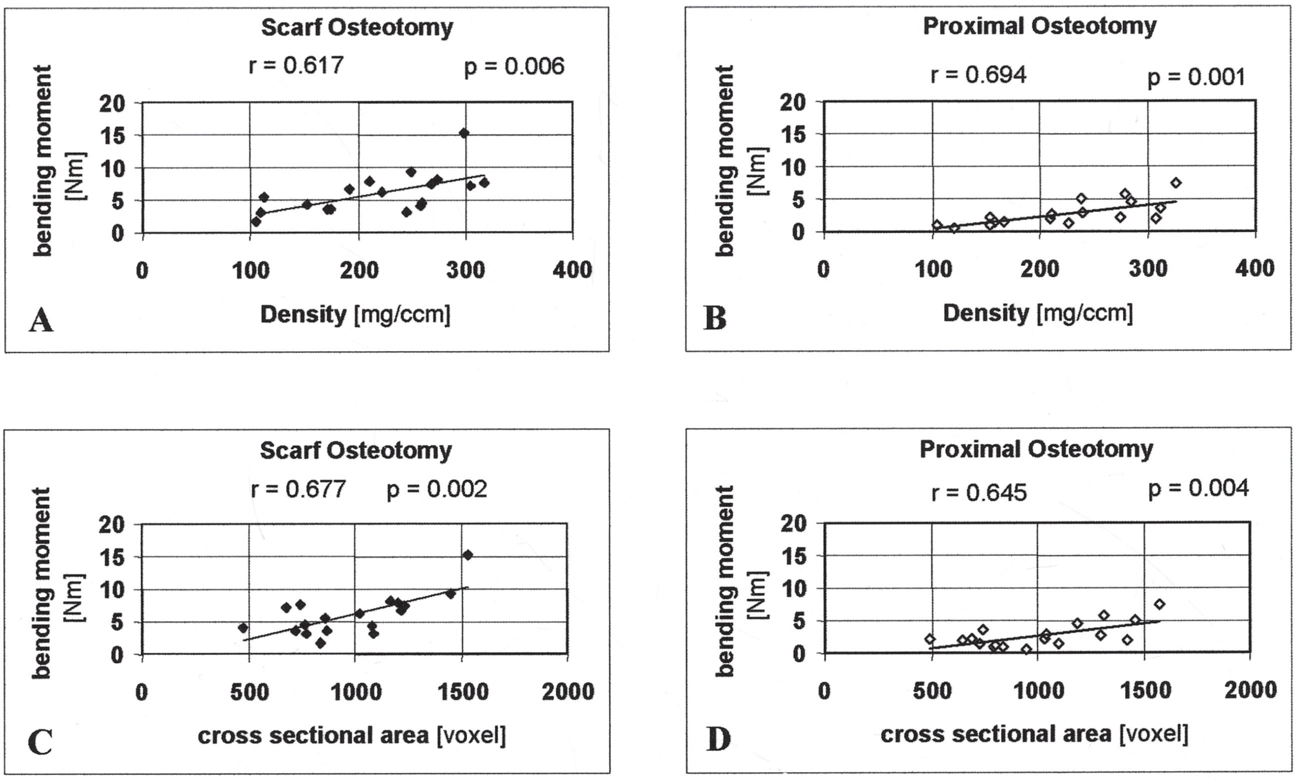

Fig. 6. The positive correlation between bone mineral density as well as biometrical parameters and the bending moments indicate their influence on the postoperative stability of the first metatarsal.

Discussion

The study clearly demonstrates that the postoperative stability of metatarsals after a diaphyseal (Scarf) osteotomy is considerably higher than that achieved with Proximal osteotomy. The clinical presumption that Proximal osteotomy leads to more unstable results than a more distally located ostetomy is confirmed. According to Lian et al. (1992), this is due to the greater torsional or bending moment resulting from a longer lever arm in Proximal osteotomies. Duke (1992) regards the Scarf osteotomy as a useful alternative for the treatment of severe hallux valgus deformity. Although the Proximal osteotomy corrects the intermetatarsal angle excellently, the fixation of the bone fragments is less stable due to the oblique screw position. On the other hand, the Scarf osteotomy is much more stable but does not refer to large intermetatarsal angles (Trnka et al., 2000).

The results presented in this biomechanical study revealed an ultimate load of 160.39 N for the Scarf osteotomy and 70.89 N for the Proximal one. Stamatis et al. (2003) performed similar studies to test the Ludloff metatarsal osteotomy. According to Goh et al. (1989) and Linde and Sorensen (1993), the freezing of bones does not have any effect on mechanical characteristics while fixation with formalin reduces stability to about 50%. Campbell et al. (1998) analysed 10 matched bone pairs and obtained similar values of maximum strain using deep frozen stored first metatarsals. He recommended mechanical bone fixation within the testing device at the level of the navicular bone. In our tests, the charged metatarsals were embedded in polymethylmetacrylate at their proximal base to provide a stable mechanical fixation of the bone. The graphs of loading deformation of the metatarsals revealed a different mode for failure of the charged bone on comparing the two methods. However, in both methods the failure occurred in the proximal third of the bone. Consistent with the data of Muehlemann et al. (1999), we were able to confirm the lower mineral density values in this more susceptible region in comparison with the diaphysis of the bone. Moreover, the current results indicate an age- and sex-independent increase in mineralization due to a more developed cortical layer in the diaphyseal zone. We therefore assume that the greater stability of metatarsals after diaphyseal osteotomies is based on the better bone quality in this region. On the other hand, the sparse cortical layer in the proximal third of the bone may be responsible for the gradual slackening of the osteosynthetic screw in the case of the Proximal osteotomy. Moreover, the enhanced stability of Scarf osteotomies is thought to be due to the z-shaped design. The contact area between the fragments is larger than in the proximal method and its orientation is parallel to the plane of weight bearing. Two screws transfer the compressing forces on the fragments and thereby prevent their rotation (Kalish and Spector, 1994).

Since the bending moments, calculated from force and lever arm, were individually different within both methods, other influencing factors for postoperative stability of the metatarsals should be taken into account. Alho et al. (1989) reported a clear correlation between the mineral density of a bone and its strength. Smith et al. (1992) investigated the fracture strength of the neck of fresh frozen femur bones and determined a correlation value between force and bone mineral density of about 0.8 in the medial region of the caput. Quantitative osteodensitometry has proven to be the most reliable method for estimating bone quality. Therefore it should be considered a crucial criterion to be taken into account prior to surgical procedures. Following quantitative computertomographical measurements of mineral density, Louis et al. (1995) performed compression trials on cylindrical specimens of the radius. Cortical density (r = 0.78) and thickness (r = 0.74) were significantly correlated with maximal stress on biomechanical testing. Keaveny et al. (1994) compared the computertomographically determined density values of trabecular bone cylinders from bovine proximal tibiae with the corresponding maximum pressure and tensile loadings, also finding a high correlation (r = 0.8). Our results indicate that there is no significant correlation between age at death and maximum strain of an operated bone, although it can be assumed that, in general, bone density diminishes with advancing age (Grampp, 1993). In consequence, older age should not be automatically considered as an excluding criterion for metatarsal osteotomy. Moreover, we found that the higher stability of male metatarsals on average was not only due to higher bone mineral density but also to the greater cross-sectional areas. Nevertheless, the latter factor is only one of several parameters defining the individual geometry of the bone.

Finally, the metatarsals corrected by Scarf osteotomy were characterised by a significantly higher stability as compared with the proximal-corrected ones. Therefore, the Scarf osteotomy in the clinical setting could be estimated as mechanically superior. Nevertheless, individual variables -such as the mineral density and geometry of the bone- must be taken into account.

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