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Abstract

Background: We performed a biomechanical comparison of 2 methods for operative stabilization of pronation-abduction stage III ankle fractures; group 1: Anterior-posterior lag screws fixing the posterior tibial fragment and lateral fibula plating (LSLFP) versus group 2: locked plate fixation of the posterior tibial fragment and posterior antiglide plate fixation of the fibula (LPPFP).

Methods: Seven pairs of fresh-frozen osteoligamentous lower leg specimens (2 male, and 5 female donors) were used for the biomechanical testing. Bone mineral density (BMD) of each specimen was assessed by means of dual-energy x-ray absorptiometry. After open transection of the deltoid ligament, an osteotomy model of pronation abduction stage III ankle fracture was created. Specimens were systematically assigned to LSLFP (group 1, left ankles) or LPPFP (group 2, right ankles). After surgery, all specimens were evaluated via CT to verify reduction and fixation. Axial load was then applied onto each specimen using a servohydraulic testing machine starting from 0 N (Zwick/Roell, Ulm, Germany) at a speed of 10 N/s with the foot fixed in a 10 degrees pronation and 15 degrees dorsiflexion position. Construct stiffness, yield, and ultimate strength were measured and dislocation patterns were documented with a high-speed camera. The normal distribution of all data was analyzed using Shapiro-Wilk test. The group comparison was performed using paired Student t test. Statistical significance was assumed at a *P* value of .05.

Results: All specimens had BMD values consistent with osteoporosis. BMD values did not differ between the left and right ankles of the same pair (*P* = .762). The mean BMD values between feet of men (0.603 g/cm²) and women (0.329 g/cm²) were statistically different (*P* = .005). The ultimate strength for LSLFP (group 1) with 1139 ± 669 N and LPPFP (group 2) with 2008 ± 943 N was statistically different (*P* = .036) as well as the yield in LSLFP (group 1) 812 ± 452 N and LPPFD (group 2) 1292 ± 625 N (*P* = .016). Construct stiffness trended to be higher in group 2 (179 ± 100 kNn) compared to group 1 (127 ± 73 kN/m) but this difference was not statistically significant (*P* = .120). BMD correlated with bone-construct failure.

Conclusion: Fixation of the posterior tibial edge with a posterolateral locking plate resulted in higher biomechanical stability than anterior-posterior lag screw fixation in an osteoporotic pronation-abduction fracture model.

Clinical Relevance: The clinical implication of this biomechanical study is that the posterior antiglide plating might be advantageous in patients with osteoporotic pronation abduction stage III ankle fracture.

Keywords: biomechanical, ankle fracture, osteoporotic bone, posterior antiglide plating, posterior tibial fragment

Introduction

Ankle fractures are among the most frequent fractures in elderly women, with an increasing incidence.^{13,15,24,47} Based on Lauge-Hansen's classification, a recent investigation with a large number of patients revealed the pronation-abduction (PA) fracture (20.2%) to be the second most frequent ankle fracture in contrast to a former study of Lauge Hansen (with only 7%).^{4,19,47} Thus, the highly unstable PA

fracture is a typical injury in the elderly, especially in women older than 60 years.⁴⁷ The commonly seen dislocation mechanism in PA fracture regularly compromises the soft tissues, mainly around the medial malleolus, and osteoporotic bone quality potentially compromises fixation stability, leading some authors to alter their standard surgical technique.^{29,39} The standard fixation technique includes using a lateral approach to the fibula followed by direct open reduction, lag screw fixation, and lateral neutralization plating of the fibula

followed by indirect reduction of the posterior malleolus fracture and fixation with anterior to posterior (A-P) lag screws.

High complication rates are reported with closed manipulation and standard fixation techniques in osteoporotic ankle fractures. Post-traumatic arthritis, loss of reduction, skin necrosis, nonunion, and malunion represent some of the commonly seen major complications in this fracture type.^{27,33,36-38,45}

In biomechanical studies, posterior antiglide plating of the fibula via a posterolateral approach in distal fibular fractures and posterolateral plating of the posterior malleolus leads to more stable fixation of a trimalleolar ankle fracture model.^{23,25} This technique might reduce complication rates by improving anatomic reduction of the posterior malleolar fracture leading to better joint mechanism, articular congruity, and functional stability.^{1,3,4,7,42} We hypothesized that the posterolateral technique (posterior fibular antiglide plate and posterior buttress-plating of the posterior malleolus) would provide a more stable construct than the conventional technique (lateral fibular neutralization plate and A-P lag screw fixation of the posterior malleolus) in osteoporotic pronation abduction stage III fracture model. To our knowledge, this is the first biomechanical study comparing these 2 fixation methods.

Material and Methods

Seven pairs (2 male and 5 female) of fresh-frozen osteoligamentous lower leg specimens were used for this study. The age of the donors ranged from 71 to 89 (mean 85) years, and weight ranged from 40 to 85 (mean 61) kg. Specimens were stored at -20°C until thawing for 24 h at room temperature prior to testing.

All specimens were evaluated for bone mineral density (BMD) before the operation with a PIXI device (GE Lunar, Madison, WI) using a dual-energy x-ray absorptiometry (DXA) method. Lateral (sagittal) scans of the central part of the calcaneal tuberosity were obtained to assess BMD. According to the original software (Pixi 2.0) the average value for the whole population is approximately 0.510 g/cm^2 in women and 0.620 g/cm^2 in men. Abnormal range for the skeletal location for PIXI measurements is defined by a T score ≤ 1.6 (WHO fracture risk equivalent). All bony and ligamentous structures of the foot were left intact. Soft tissues were left intact. A lateral and posterolateral approach

Figure 1. (A) Oblique distal fibular osteotomy with resection; (B) view of the posterolateral tibial lip.

to the ankle joint was performed as well as for sectioning the superficial and deep portions of the deltoid ligament medially. A PA stage III equivalent fracture was simulated by a standardized oblique distal fibular osteotomy (with resection of a 7-mm shaft segment to simulate comminution) and an oblique osteotomy of the posterolateral tibial lip in the same plane (Figure 1). The deep and superficial portion of the deltoid ligament was sectioned via a medial approach in all feet. Fractures were then anatomicallly reduced and fixed following the protocol.

Left feet were operated according to the standard AO/ASIF technique,³⁴ using a lag screw and lateral fibula 6-hole semitubular neutralization plate ($7.5 \times 0.9\text{ cm}$) (Synthes GmbH, Oberdorf, Switzerland). The plate was fixed with three 3.5-mm bicortical screws proximal and two 3.5-mm bicortical screws distal to the fracture via a lateral approach (Figure 2A). Indirect reduction of the posterior malleolus was performed and fixation obtained with 2 A-P 3.5-mm lag screws (Synthes, Oberdorf, Switzerland). Right feet were operated using a posterolateral approach. The posterior malleolus was reduced anatomicallly first and fixed with a posterior anatomicallly preshaped tibial locking T-plate (Intercus GmbH, Bad Blankenburg, Germany) (Figure 2B). Via the same approach, the fibula was reduced anatomicallly and a 6-hole semitubular fibular antiglide plate was fixed to the bone with 2 screws distally and 3 screws proximally (Figure 2B). The soft tissues around the fractures were left open giving the opportunity to visualize fixation failure. After surgery, all specimens were evaluated for correct reduction and fixation with CT scanning (Figure 2).

Biomechanical testing was done in a Zwick/Roell servohydraulic testing machine (Zwick/Roell Z010 TN, Zwick, Ulm, Germany). The proximal tibia-fibula complex was potted and fixed in a specially designed cylindrical holder filled with polymethylmethacrylate (PMMA).

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Figure 2. Computed tomographic scan after fracture fixation: (A) anterior-posterior lag screws fixing the posterior tibial fragment and lag screw lateral fibula plating (LSLFP), 1: arrow shows the fibular defect; (B) locked plate fixation of the posterior tibial fragment and locking plate posterior fibula plating (LPPFP), 2: oblique plan of posterior malleolus osteotomy.

Pronation position was defined as the purely lateral slope of the foot with respect to the tibia in the frontal plane.^{10,18}

Figure 3. Fixed specimen in the custom-made static foundation in the testing machine (Zwick/Roell).

The entire foot distal to the ankle was rigidly fixed to a custom-made metal testing plate in 15 degrees of dorsiflexion to produce the most strain on the ankle mortise and 10 degrees of pronation in order to produce a pronation-abduction type fracture.¹⁰ The foot was fixed to the plate with two 6.0 Steinman pins for the forefoot and calcaneus and two 6.0 Schanz screws for the anterior and posterior portion of the talus still allowing free movement of the subtalar and ankle joints. Load was applied to the cylinder through a sphere, allowing 3-dimensional freedom of the construct without any torque and bend movement protection (Figure 3). The plate and foot were tightly fixed to a custom-made pedestal in 10 degrees of pronation and 15 degrees of dorsiflexion. Before loading, the tibia was positioned perpendicular over the talar trochlea and in line with the prop of the testing machine. The testing sequence consisted of applying an axial load at a speed of 10 N/s starting from 0 N force until failure of the construct. Load and strain were registered automatically by the software of the testing machine. The whole testing process was monitored by a high-speed videocamera to assess failure patterns.

Figure 4. Stiffness of construct. Fixation with the locking plate and posterior fibula plating (group 2) showed a higher stiffness ($P = .120$).

Construct stiffness was defined as the slope of the initial linear region of the load versus displacement curve, whereas elastic limit (yield) was defined as a point (N) where the linear slope of the force (N) versus displacement (mm) curve ended. Finally, ultimate strength was defined as the point of major discontinuity (sharp decrease in the load/displacement curve). Inspection and videomaterial obtained by the videocamera were analyzed in order to understand and document the sequence of construct failure. Parameters were tested for normal distribution using the Shapiro-Wilk test. Differences between the groups were analyzed using the paired Student *t* test. Statistical significance was set at a *P* value of .05. The outcome parameters assessed were stiffness, elastic limit (yield), and ultimate strength. The data for the ultimate strength were also correlated to BMD with a standard correlation procedure (Pearson correlation).

Results

No abnormalities such as peri-implant fracture, failure of interfragmentary screws, joint penetration of screws, and malreduction or malposition of screws were detected in any of the 14 specimens using visual inspection and CT scanning.

All feet displayed osteoporotic bone quality with a mean BMD of 0.407 g/cm². In female feet, a mean BMD of 0.329 ± 0.069 g/cm² was measured and a mean BMD of 0.603 ± 0.027 g/cm² in males. In female specimens, the lowest BMD was 0.214 g/cm² and the highest 0.437 g/cm². In male donors, the lowest BMD was 0.561 g/cm² and the highest BMD was 0.629 g/cm². A significant difference ($P = .005$) in mean BMD between feet of men and women as well as in mean age between feet of men and women (Table 1) was found. No significant difference in BMD data were observed between the 2 groups (Table 2) and between the left and right foot of any specimens.

We determined the mechanical stability of fixation methods to be a function of BMD. The maximal force to

failure of the LSLFP group correlated more with the BMD than the LPPFP group ($r^2 = 0.012$; $P = .0013$ for the LPPFP group; $r^2 = 0.609$; $P = .0036$ for the LSLFP group). Qualitatively, the data showed that locked plating resulted in significantly higher forces to failure in specimens that had diminished BMD than screw fixation ($P = .036$) (Table 2).

Postoperative CT scans revealed anatomic reduction of all fibulae (both groups) and for the posterior malleolus in the LPPFP group. In the LSLFP group, the posterior malleolus was in 5 to 10 degrees external rotation malalignment and 1 to 2 mm shortened in 4 of 7 specimens.

We found a statistically significant difference in elastic limit (yield) and ultimate strength at failure between both groups (Table 2). The elastic limit of the LPPFP group was significantly higher (1292 ± 625 N) compared with the LSLFP group (812 ± 452 N) ($P = .016$). The LPPFP group showed an approximately 59% higher elastic limit in comparison to the LSLFP group. Ultimate strength was significantly higher in the LPPFP group (2008 ± 943 N) compared with the LSLFP group (1139 ± 669 N) ($P = .036$). Stiffness was 41% higher in the LPPFP group compared with the LSLFP group, but this difference was not statistically significant ($P = .120$). Reaching ultimate load to failure, the LSLFP group showed failure of fixation in 5 of 7 (71.4%) constructs and the LPPFP group in 1 construct (14.3%). The primary failure pattern was a failure of the fibular fixation in all constructs. One of the ankles of the LPPFP group showed a dislocation of the posterior locking T-plate, whereas in the LSLFP group all ankles showed a dislocation of the posterior malleolus.

Discussion

Based on the Lauge-Hansen classification, the PA fracture represents the second most frequent fracture and occurs frequently in elderly women.^{19,47} Several studies have shown that open reduction and internal fixation results in better outcomes than nonoperative treatment in elderly patients.^{2,28} Numerous clinical and biomechanical studies deal with surgical strategies for the fixation of osteoporotic bone.^{5,6,16,23,31,35,46} PA fractures are highly unstable and need exact anatomic reduction and sufficient stabilization, especially in osteoporotic bone. We therefore established a cadaveric model for biomechanical analysis of 2 fixation methods for osteoporotic unstable PA fractures. Our hypothesis was that the direct posterolateral technique with antiglide plating and locked plating of the posterior tibial fragment would have a favorable biomechanical effect in comparison with the lateral approach and indirect fixation with A-P screws. Our findings support this hypothesis.

In summary, we found higher yield and ultimate strength in the ankles fixed from posterior. With both techniques, dislocation of the fibular plate was identified as the mechanism of fixation failure. However, in the antiglide plate group

Table 1. Characteristics of the Groups.^a

	Female, Mean $\pm$ SD	Male, Mean $\pm$ SD	P Value
BMD of the specimen (g/cm ²)	0.329 $\pm$ 0.069	0.603 $\pm$ 0.027	.005
T score of the specimen	-1.9 $\pm$ 1.1	-0.2 $\pm$ 0.6	.017
Age of the donor (y)	89.2 $\pm$ 4.8	80.5 $\pm$ 2.9	.006

Abbreviations: BMD, bone mineral density; SD, standard deviation.

^at test for independent variables, grouping variable: sex tabulated summary of mean $\pm$ standard error the BMD of gender and groups of specimens. All values showed a significant difference between female and male. The BMD and t-score of females are much lower than males and might indicate the osteoporotic bone.

Table 2. Summary (mean $\pm$ standard deviation) of Biomechanical Parameters and Statistical Significance of Specimens, Mean BMD of Specimens.

	LSLFP Group 1	LPPFP Group 2	P Value
Stiffness, kN/m	127 $\pm$ 73	179 $\pm$ 100	.120
Elastic limit (yield), N	812 $\pm$ 452	1292 $\pm$ 625	.016
Ultimate load to failure (strength), N	1139 $\pm$ 669	2008 $\pm$ 943	.036
Mean BMD of the specimen, g/cm ²	0.406 $\pm$ 0.114	0.409 $\pm$ 0.129	.762

Abbreviations: BMD, bone mineral density; LPPFP, locked plate fixation of the posterior tibial fragment and posterior antiglide plate fixation of the fibula; LSLFP, anterior-posterior lag screws fixing the posterior tibial fragment and lateral fibula plating. Stiffness of LPPFP (group 2) showed higher values, but was not statistically significant. The mean BMD of the specimen showed no significant difference between the constructs.

(LPPFP), this failure was only seen in 1 of 7 ankles, whereas in the lateral plated group (LSLFP), this was observed in 5 of 7 ankles. The load to failure required in the LPPFP group was twice as high as in the LSLFP group. Only 1 ankle of the LPPFP group showed a dislocation of the posterior plate at ultimate strength whereas in all 7 ankles of the LSLFP group a dislocation of the posterior malleolus was observed when reaching ultimate strength. Stiffness was found to be higher in LPPFP group compared with the LSLFP group, but this difference was not statistically significant. One possible explanation could be the relatively low number of specimens. Another reason could be the exclusive axial loading. An additional torque or cyclic load could have led to a significant difference between the groups.

In our study, all specimens had BMD values consistent with osteoporosis. The mean BMD between feet of men and women was statistically different ($P = .005$) but the BMD correlated with bone-construct failure. The ultimate strength and yield were significantly higher in the LPPFP group.

Similar to our study, Kim et al and Zahn et al, in their biomechanical studies, could not detect a statistically significant difference in stiffness between locking and unlocking plates of the distal fibula.^{16,46} Also, the failure of the conventional plates was dependent on BMD whereas failure of locking plate fixation was independent of BMD. These data are in accordance with our findings, that the LPPFP fixation technique with a locking plate for the posterior tibial fragment results in an increased load to failure in osteoporotic bone.

Our study confirms the findings made by various authors that the more osteoporotic the ankle the higher the risk of

failure under load.^{6,15,16,23,35,46} At present, BMD values for the distal tibia or fibula defining osteoporosis do not exist. We therefore measured the BMD of the calcaneus assuming that a low BMD in the calcaneus is consistent with generalized osteoporosis.^{8,20} Female donors displayed a significantly lower BMD than male donors. In the present study, force to failure was identified as a function of BMD. The stability of the construct with standard fixation technique (LSLFP group) was found to be more dependent on BMD than that of the LPPFP group. These data indicate that locked plating increased the load to failure, especially in osteoporotic bone as also suggested by other biomechanical studies.^{16,23,46} Our clinical experience with failure of fixation and soft tissue complications when employing standard plating fixation in osteoporotic patients mimics these results.³² In contrast, the failure load of the locking plate (LPPFP group) was less dependent on the BMD.

In biomechanical studies, the stages of the Lauge-Hansen classification could not be reproduced exactly. Pronation only was not sufficient to produce a typical PA fracture pattern.^{9,10,11,32,35} We chose the pronation dorsiflexion position of the foot in our biomechanical testing because we assumed that dorsiflexion in combination with pronation is essential for producing this dislocated fracture as it puts increased stress on the dorsal syndesmotom ligament. Hence, maximum stability of fixation is necessary to withstand loading at the time of impact. Michelson et al showed that an additional valgus load to the fibula in dorsiflexion could induce a typical SE fracture.²¹ Haraguchi et al supported their results showing that most ankle fractures are associated with pronation of the foot.¹⁰

There is still no consensus on the indication for fixation of the posterior malleolus fracture and the optimal fixation technique.^{12,14,22} But van den Bekerom et al, Raasch et al, and other authors consider that the existence of a posterior tibial fragment in ankle fractures causes instability and thus needs fixation.^{30,41}

As shown by O'Connor et al, stable fixation of an anatomically reduced posterior malleolus is an important criterion for ankle stability when treating fracture-dislocations.²⁵ The biomechanically positive effect of a posterior fibular antiglide plate compared to a lateral fibular plate as well as the positive effect of locked compared to conventional plating in osteoporotic ankle fractures has been demonstrated by various authors.^{16,23,35,44,46} To our knowledge, our study is the first to demonstrate the biomechanical advantage of combined posterior fibular and posterior malleolar plating compared to lateral fibular plating and A-P lag screw fixation of the posterior malleolus in ankle fracture dislocations. Implant costs for a locking plate are higher than those for conventional screws. However, the prevention of implant failure in osteoporotic bone has the potential to avoid secondary surgery with much higher costs. The surgery time is expected to be slightly higher in posterior plating versus A-P screws. On the other hand, indirect reduction may be more difficult to achieve in the latter, which in turn will prolong surgery time with the use of A-P screws.

Besides increased stability, locking plate fixation via a posterior approach could minimize soft tissue problems. The posterolateral approach offers the advantage of soft tissue protection through the long and short peroneals and flexor hallucis longus muscles, whereas with the lateral approach, the plate is only covered by skin and any fixation failure could compromise the skin.³ The potential irritation of the peroneal tendons with a far distal placement of a posterior fibular plate should be nevertheless kept in mind.⁴³

With both techniques, anatomic fixation of the posterior malleolus and syndesmotic ligament stability is crucial. Postoperative malposition is associated with inferior results, and therefore syndesmotic malreduction warrants reoperation.²⁷ Overall in osteoporotic ankle fractures with critical soft tissue injury, posterolateral antiglide plating appears biomechanically more stable than the conventional technique with lateral plating of the fibula and A-P screws.^{17,23,26,35,40}

This study has several limitations. One is the relatively low number of specimens used in this study although a statistically significant difference was demonstrated. The use of cadaver specimens is more valid than the use of a saw-bone model. However, the integrity of the bone structure in vitro may be different than in vivo and there is no active muscular control. Furthermore, as with any cadaveric testing, we could only explore initial fixation and not bone

healing. Also, the loading pattern was pure axial loading as opposed to the more complex loading patterns seen in gait that cannot be reliably reproduced in a biomechanical setting. Finally, because of our osteoporotic biomechanical model, we loaded to failure because in osteoporotic ankles a catastrophic failure could be expected. In normal bone, most fracture fixation would fail gradually with axial loading. In the future, comparative clinical studies are needed to answer the question whether the observed biomechanical advantages of posterior plating for fracture of the posterior tibial rim translates into better outcomes in these patients.

Conclusion

In summary, we have demonstrated the biomechanical advantages of posterior antiglide plating of the distal fibula and posterior locking plate fixation for the posterior tibial fragment in comparison to the conventional technique using a lateral fibular plate and anterior-posterior lag screws for the posterior tibial fragment. Using a posterior plate resulted in twice as high load to failure and elastic limit compared to the conventional method. Clinically, this approach may be advantageous in patients with severe osteoporosis.

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