A biomechanical comparison of fixed angle locking compression plate osteosynthesis and cement augmented screw osteosynthesis in the management of intra articular calcaneal fractures

Sascha Rausch · Kajetan Klos · Uwe Wolf · Marc Gras ·
Paul Simons · Steffen Brodt · Markus Windolf ·
Boyko Gueorguiev

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Abstract

Purpose The purpose of this study was to investigate whether cement-augmented screw osteosynthesis results in stability comparable to conventional fixed-angle locking plate osteosynthesis using cadaveric bones to model a Sanders type 2B fracture.

Methods Seven pairs of fresh frozen human calcanei and the corresponding tali were used. The specimens were assigned pairwise to two study groups in a randomised manner. In order to determine the initial quasi-static stiffness of the bone-implant construct, testing commenced with quasi-static compression ramp loading; subsequently, sinusoidal cyclic compression loading at 2 Hz was performed until construct failure occurred. Initial dynamic stiffness (cycle 1), range of motion (ROM), cycles to failure and load to failure were determined from the machine data during the cyclic test. In addition, at 250-cycle intervals, Böhler's angle and the critical angle of Gissane were determined on mediolateral X-rays shot with a triggered C-arm; 5° angle flattening was arbitrarily defined as a failure criterion.

Results Bone mineral density was normally distributed without significant differences between the groups. The

augmented screw osteosynthesis resulted in higher stiffness values compared to the fixed-angle locking plate osteosynthesis. The fracture fragment motion in the locking plate group was significantly higher compared to the group with augmented screw osteosynthesis.

Conclusions The results of this study indicate that in our selected test set-up augmented screw osteosynthesis was significantly superior to the conventional fixed-angle locking plate osteosynthesis with respect to primary stability and ROM during cyclic testing.

Keywords Calcaneal fracture · Plate osteosynthesis · Augmented screws · Biomechanics · Cadaver study

Introduction

Plate osteosynthesis through a lateral approach is currently considered the gold standard for surgical management of calcaneal fractures [1–3]. This technique is associated with a high incidence of soft tissue complications [4, 5]. It is not surprising that minimally invasive techniques such as screw osteosynthesis are gaining increasing popularity [6–8]. On the other hand, minimally invasive techniques should not be resorted indiscriminately at the expense of anatomical reduction. Advancements in surgical techniques (e.g. mini-open) and the increasing intra-operative use of state-of-the-art imaging (3D scans, computed tomography) as well as the use of arthroscopy contribute to improved outcomes [9]. A continuing problem is that the calcaneal anatomy makes adequate stabilisation of the fracture difficult to achieve because the “neutral zone” may have extensive bone defects, particularly in impaction fractures and their reduction [10, 11]. Despite the use of locking compression plate osteosynthesis, inadequate stabilisation leads to protracted non-weight-bearing and

S. Rausch (✉) · U. Wolf · M. Gras
Klinik für Unfall-, Hand-, und Wiederherstellungschirurgie,
Friedrich-Schiller-Universität, Jena, Germany
e-mail: sascha.rausch@med.uni-jena.de

K. Klos · P. Simons
Abteilung für Fuß- und Sprunggelenkschirurgie, Katholisches
Klinikum Mainz, Mainz, Germany

S. Brodt
Klinik für Unfallchirurgie, St. Georg Krankenhaus Leipzig, Leipzig,
Germany

M. Windolf · B. Gueorguiev
AO Research Institute Davos, Davos, Switzerland

partial weight-bearing of the affected limb as well as to osteosynthesis failure. Thus, several biomechanical and clinical studies have been performed to evaluate various augmentation methods using bone cement [12–16].

The purpose of this study was to investigate whether cement-augmented screw osteosynthesis results in stability comparable to conventional fixed-angle locking plate osteosynthesis using cadaveric bones to model a Sanders type 2B fracture. The null hypothesis was that cement-augmented screw osteosynthesis was not inferior to the locking plate osteosynthesis with regard to construct stiffness, range of motion (ROM) and load to failure.

Materials and methods

Specimens, study groups and set-up for biomechanical testing

In this study, seven pairs of fresh frozen ($-20\text{ }^{\circ}\text{C}$) human calcanei and the corresponding tali were used (mean age 81 years, range 61–89 years, four men and three women). The study was approved by the Ethics Committee. The calcaneal bone mineral density was measured with dual-energy X-ray absorptiometry scans (Hologic QDR 4500 Elite, Hologic, Bedford, MA, USA) in a standardised manner. Paired comparisons were performed. In all bone specimens, a reproducible Sanders type 2B fracture [11, 14, 16] (Fig. 1) was created with a bandsaw (CMI, OBI Merchandise Center GmbH, Wermelskirchen, Germany), and a defined impaction (thalamic portion, neutral triangle) was created using a blunt chisel (2.5 cm) (Fig. 2) [14].

The specimens were assigned pairwise to two study groups in a randomised manner for either plate or screw osteosynthesis. The procedure involved a skilled surgeon fixing one calcaneus of a pair with a uniaxial fixed-angle locking plate (3.5 mm LCP, DePuy Synthes, Solothurn,

Fig. 1 Left calcaneus with a Sanders type 2B fracture (marked)

Fig. 2 Neutral triangle and blunt chisels employed

Switzerland) and the corresponding contralateral calcaneus with screw osteosynthesis using two cannulated double-threaded headless compression screws (6.5 mm HCS, DePuy Synthes, Solothurn, Switzerland) and two sustentaculum screws (KFI, 3.5 mm, DePuy Synthes, Solothurn, Switzerland). The screw osteosynthesis specimens were augmented in the area of the simulated defect. Augmentation was accomplished using 2.5 ml polymethyl methacrylate (PMMA) cement (Traumacem V+, DePuy Synthes, Solothurn, Switzerland) injected through the lateral fracture fissure using a Trauma Needle Kit (DePuy Synthes, Solothurn, Switzerland) (Figs. 3 and 4).

A custom test set-up was used [14] (Fig. 5). The load was applied to the posterior talar articular surface of the calcaneus through the talus in a specific talotarsal joint position, standardised during the embedding procedure. Each bone specimen was embedded in medium comprising a two-component acrylic plastic (PMMA, Beracryl, Troller AG, Fuluibach, Switzerland). The specimens were mounted on the testing machine at the calcaneal tuberosity and the anterior process via cylindrical jigs. These were additionally placed on slides (Schneeberger Company, Roggwil, Switzerland) to enable transverse plane movements of the specimens in addition to possible sintering. Biomechanical testing was performed on a servohydraulic testing machine (Bionix, model 858.20,

Fig. 3 Comparative computed tomography reconstruction of both types of osteosyntheses in the neutral triangle area

Fig. 4 Three-dimensional computed tomography imaging of a left calcaneus with augmented screw osteosynthesis

MTS Systems, Eden Prairie, MN, USA) with a 25 kN/200 Nm load cell.

Loading protocol and data evaluation

In order to determine the initial quasi-static stiffness of the bone-implant construct, testing commenced with quasi-static compression ramp loading, starting at 20 N and increasing to 200 N at a rate of 18 N/s. Subsequently, sinusoidal cyclic compression loading at 2 Hz was performed until construct failure occurred. The valley load was maintained at a constant level of 50 N during the entire cyclic test, and the peak load was increased cycle by cycle at a rate of 0.06 N/cycle, starting at 200 N (cycle 1). Cyclic testing with monotonically increasing load levels proved to be useful in previous studies [17, 18]. Initial dynamic stiffness (cycle 1), ROM, cycles to failure and load to failure were determined from the machine data during the cyclic test. The ROM was calculated as the difference between the minimum and maximum deformation during one cycle at the start of testing and periodically at intervals of 1,000 cycles up to 5,000 cycles. In addition, at 250-cycle intervals, Böhler's angle and the critical angle of Gissane were determined on mediolateral X-rays shot with a triggered C-arm (Figs. 6, 7); 5° angle flattening was arbitrarily defined as a failure criterion.

Fig. 5 Test set-up with a right calcaneus and talus bone specimen

Statistical analysis

Statistical analysis was performed using SPSS (IBM SPSS Statistics, Chicago, IL, USA). The normal distribution in each study group was evaluated using the Shapiro-Wilk test. The paired-samples *t* test was applied to identify significant differences between the groups with respect to bone mineral density, initial quasi-static and dynamic construct stiffness, ROM, cycles to failure and load to failure. In addition, general linear model repeated measures was used to check for significant progression of changes in ROM during the first 5,000 cycles of the cyclic test. The significance level was set to 0.05 for all statistical tests.

Results

Bone mineral density

Bone mineral density was normally distributed without significant differences between the two groups (plate 0.481 ± 0.048 g/cm², screws 0.519 ± 0.064 g/cm²).

Stiffness

With respect to initial quasi-static and dynamic stiffness, the augmented screw osteosynthesis (276.2 ± 25.9 N/mm and 756.2 ± 55.9 N/mm, respectively) resulted in higher stiffness values compared to the fixed-angle locking plate osteosynthesis (193.4 ± 21.8 N/mm and 593.6 ± 46.7 N/mm, respectively, $p=0.017$ and $p=0.039$, respectively).

Fig. 6 Example of radiological imaging during biomechanical testing of a specimen with plate osteosynthesis

Fig. 7 Example of radiological imaging during biomechanical testing of a specimen with augmented screw osteosynthesis

Range of motion

With respect to ROM at the start of the cyclic test (cycle 1) and periodically at intervals of 1,000 cycles up to 5,000 cycles, the fracture fragment motion in the locking plate group was significantly higher compared to the group with augmented screw osteosynthesis ($p \leq 0.039$, Table 1). In addition, in contrast to the screws, the plate osteosynthesis showed a significant increase of ROM between 2,000 and 5,000 cycles ($p \leq 0.033$).

Failure

With respect to cycles and load to failure, and failure mode, no significant differences between the groups in terms of the number of cycles to failure and hence load to failure were revealed from Böhler's angle or Gissane's angle 5° failure criteria ($p = 0.774$ and $p = 0.865$, respectively). The characteristic failure patterns are depicted in Fig. 8.

Discussion

The purpose of this study was to compare the biomechanical properties of conventional fixed-angle locking compression

plate osteosynthesis and cement-augmented screw osteosynthesis in an established intra-articular calcaneal fracture model [14]. With respect to stiffness and ROM, augmented screw osteosynthesis specimens displayed significant advantages, whereas regarding the load to failure (Böhler's angle, Gissane's angle $>5^\circ$) no significant differences were revealed. Hence, we confirmed the null hypothesis that cement-augmented screw osteosynthesis is not inferior to the locking plate osteosynthesis with regard to construct stiffness, ROM and load to failure.

Several biomechanical studies of different fracture types, various implants and test set-ups have been performed so far [11, 14, 16, 19, 20]. The osteosynthesis failure mechanism with loss of reduction of the weight-bearing joint surface and dislocation of the anterior process of the calcaneus, described in these studies, was reproduced with our testing set-up and loading protocol [20, 21].

Fixed-angle locking compression plate osteosynthesis through the lateral approach is currently the gold standard procedure for the surgical management of calcaneal fractures [1–3]. The extensile lateral approach, however, is often associated with soft tissue complications [4, 5]. Minimally invasive treatment modalities have been established to avoid these complications, and, when performed by skilled surgeons, the clinical results are comparable and the risk of abnormal wound healing is lower [7, 8, 13, 22–24]. Furthermore, Chen et al. concluded that minimally invasive screw osteosynthesis augmented with calcium sulphate cement results in a more rapid return to weight-bearing, diminished joint stiffness and increased patient satisfaction [13]. Kline et al. prefer the minimally invasive surgical modality due to their positive experience primarily in patients with an increased risk of abnormal wound healing [23].

In addition to the soft tissue advantages, the choice of optimal osteosynthesis of an intra-articular calcaneal fracture should be based on consideration of the technical feasibility, the ability to verify reduction results intra-operatively and the quality of retention [2]. The weight-bearing talotarsal joint is exposed to large biomechanical forces and requires stable subchondral support to enable functional treatment with early weight-bearing. In this regard, fixed-angle locking plates offer a significant advantage over conventional plates [11]. Nevertheless, the problem of the eccentric position of the plate with respect to the zone of maximum stress remains. The screw osteosynthesis investigated in our study is theoretically associated with biomechanical advantages offered by the positioning of various screws and augmentation directly in the area of maximum stress.

The results of this study confirm this view. The novel element in the technique used in our study is the rigid connection between the double-threaded screws positioned centrally below the joint surface and the bone cement that practically encases the screws spanning the defect. Proper selection of the screw length resulting in securely anchored screw

Table 1 ROM (mm) in the locking plate group (plate) compared to the group with augmented screw osteosynthesis (screws)

Cycle		1 (initial)	1,000	2,000	3,000	4,000	5,000
Plate	Mean	0.256	0.273	0.302	0.335	0.440	0.510
	SEM	0.023	0.025	0.025	0.027	0.039	0.047
Screws	Mean	0.187	0.204	0.219	0.255	0.328	0.337
	SEM	0.011	0.015	0.013	0.023	0.035	0.036
<i>p</i> value		0.014	0.033	0.011	0.015	0.039	0.016

Fig. 8 Characteristic failure patterns. Plate osteosynthesis (**a, b**) shows a compression fracture of the posterior facet, typically with dislocation of the two joint fragments and dislocation in abduction. Screw

osteosynthesis failure (**c, d**) was characterised by pull-out of the longitudinal screws from the anterior process, whereas there was no dislocation of the posterior facet

threads in subchondral and/or cortical bone allow for a third interlocking with additional screw support. Vertical positioning of sustentaculum screws with respect to axial screws also contributes to increased stiffness and may prevent caving in of the joint surface and flattening of Böhler's angle. In our opinion, the decisive factor for the quality of screw osteosynthesis is the ability to obtain a distance as small as possible between the screw threads and the anterior surface of the calcaneus to ensure a good hold in the strong subchondral bone. The results of a previous study by Smerek et al. indicate comparable stiffness between conventional plate osteosynthesis and screw osteosynthesis in a similar cadaveric bone fracture model; however, the failure load was only 1.5- to 2-fold the body weight [19]. Their conclusion was that early return to full weight-bearing necessarily leads to osteosynthesis failure of both constructs [19]. Additional augmentation can further improve the already established screw osteosynthesis on the calcaneus, and an earlier weight-bearing protocol can be followed. In our test set-up, the failure criterion, defined as a 5° flattening of Böhler's or Gissane's angles, was not reached until application of a load several times higher than the body weight. This corroborates the observation by Elsner et al. who tested full weight-bearing of the augmented calcaneal osteosynthesis after four weeks and failed to observe any loss of reduction [25]. Johal et al. supported the use of an injectable, in situ hardening calcium phosphate paste to fill the bone void after a displaced intra-articular calcaneal fracture and osteosynthesis with plate and K-wires [26]. They found a significant loss of Böhler's angle in the group without augmentation after six months but no difference between the two groups in regard to clinical

outcome measures. Avoiding calcaneal collapse after weight-bearing seems to be possible with augmentation [26].

For the purpose of biomechanical testing, we used cyclic vertical loading corresponding to an in vivo situation during walking. Shear forces were not applied. Nevertheless, evaluation of such complex loading patterns leaves room for interpretation and bias. For this reason, machine data were complemented by radiological evaluation of the changes in Böhler's and Gissane's angles. This graphically objectifies the loss of reduction under loading and clearly demonstrates the failure pattern [14]. The failure pattern marked by the flattening of Böhler's angle corresponds to the real-life clinical scenario and hence validates the test set-up and loading protocol.

The biomechanical data, however, cannot be extrapolated directly to everyday clinical settings. The study employed bone specimens stripped of soft tissue and extrinsic stabilisers were not considered. Apart from the correct anatomy and physiological load transmission, it is rather difficult to reproduce comparable fracture configurations and correct biomechanical measurement. In this study, conclusive statements regarding the fracture model from the biomechanical perspective can only be made for the parameters studied in vitro: ROM, stiffness, cycles and load to failure. Whether the observed advantages of the augmented screw osteosynthesis are also reflected in the everyday clinical setting should be addressed in further research.

Conclusions

The results of this study indicate that in our selected test set-up augmented screw osteosynthesis was significantly superior to

the conventional fixed-angle locking plate osteosynthesis with respect to primary stability and ROM during cyclic testing. The biomechanical advantages justify further clinical research on minimally invasive augmented screw osteosynthesis in calcaneal fractures.

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