Biomechanical analysis of two fixation methods for proximal chevron osteotomy of the first metatarsal

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Abstract

Purpose The proximal chevron osteotomy provides high correctional power. However, relatively high rates of dorsiflexion malunion of up to 17 % are reported for this procedure. This leads to insufficient weight bearing of the first ray and therefore to metatarsalgia. Recent biomechanical and clinical studies pointed out the importance of rigid fixation of proximal metatarsal osteotomies. Therefore, the aim of the present study was to compare biomechanical properties of fixation of proximal chevron osteotomies with variable locking plate and cancellous screw respectively.

Methods Ten matched pairs of human fresh frozen cadaveric first metatarsals underwent proximal chevron osteotomy with either variable locking plate or cancellous screw fixation after obtaining bone mineral density. Biomechanical testing included repetitive plantar to dorsal loading from 0 to 31 N with the 858 Mini Bionix® (MTS® Systems Corporation, Eden Prairie, MN, USA). Dorsal angulation of the distal fragment was recorded.

Results The variable locking plate construct reveals statistically superior results in terms of bending stiffness and dorsal angulation compared to the cancellous screw construct. There was a statistically significant correlation between bone mineral density and maximum tolerated load until construct failure occurred for the screw construct ($r=0.640$, $p=0.406$).

Conclusion The results of the present study indicate that variable locking plate fixation shows superior biomechanical

results to cancellous screw fixation for proximal chevron osteotomy. Additionally, screw construct failure was related to levels of low bone mineral density. Based on the results of the present study we recommend variable locking plate fixation for proximal chevron osteotomy, especially in osteoporotic bone.

Keywords Proximal chevron · Variable locking plate · Fixation · Osteotomy · Hallux valgus

Introduction

An internal fixation is required to correct a hallux deformity permanently, which is an operation that has been described in more than 130 variations over the last 100 years. The decision to operate and which technique to apply depends on the severity of the deformity [1–5] Table 1.

From a mechanical point of view, a proximal metatarsal osteotomy can achieve a greater degree of correction compared to distal or diaphyseal osteotomies in the correction of hallux valgus deformity. Therefore, the proximal procedures are recommended for more severe hallux valgus deformities [1, 2, 6–8].

The proximal chevron osteotomy, first reported by Sammarco et al., does not simply rely on a lateral translation of the distal fragment, as with the distal chevron procedure [9] but concomitantly incorporates an opening wedge principle [9–11]. The large contact area is relatively stable, and for fixation a combination of a screw and a Kirschner wire, two screws, or a plate are recommended [2, 9–17]. Nevertheless, relatively high rates of dorsiflexion malunion of up to 17 % are reported for this procedure. This leads to insufficient weight bearing of the first ray and therefore to metatarsalgia [2].

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Table 1 Results for bending stiffness of variable locking plate fixation and screw fixation respectively. There was a statistically significant difference between the fixation methods at the first loading cycle ($p<0.05$)

Cycle		1	10	50	100	200	300	400	500	600	700	800	900	1000
Screw	<i>n</i>	10	0	0	0	0	0	0	0	0	0	0	0	0
	Mean	2.1	–	–	–	–	–	–	–	–	–	–	–	–
	SD	1.5												
Locking plate	<i>n</i>	10	7	7	7	7	6	6	6	6	6	6	6	6
	Mean	33.0	29.9	20.0	18.8	18.2	17.9	17.6	26.0	26.7	26.2	26.2	26.2	25.7
	SD	27.4	27.4	16.8	16.0	15.5	15.0	15.5	26.6	29.5	28.7	27.9	28.2	27.5

A multitude of biomechanical studies have evaluated the initial stability of various metatarsal osteotomies, not only to determine which osteotomies permit early MTP joint exercises, but also to identify those which may allow early post-operative weight bearing [2, 13, 14, 18–22].

Acevedo et al. demonstrated that there was no statistical difference in fatigue endurance between the proximal chevron and Ludloff osteotomies in a cadaver model; in a saw bone model, the proximal chevron was significantly more stable in fatigue endurance testing than the crescentic and scarf osteotomies, except for the Ludloff osteotomy [23].

McCluskey et al. noted that a proximal chevron osteotomy stabilized with screw fixation tolerated a greater load to failure than the same osteotomy with Kirschner wire fixation and the proximal crescentic osteotomy stabilized with screws [24]. Their findings are supported by Lian et al. who noted that screw fixation for proximal chevron, crescentic, and long oblique osteotomies of the first metatarsal has superior load to failure characteristics than Kirschner wire or staple fixation [25].

In a saw bone model, Jones et al. reported that plate fixation provided a stronger construct than traditional screw fixation in proximal crescentic osteotomies [26].

Recent attention has been focused on plate fixation for proximal first metatarsal osteotomies due to the advent of locking plate systems and their considerable success elsewhere in the body. Also, a number of authors provided clinical and biomechanical data for these implants in foot and ankle surgery [7, 20, 27–29]. However, to the best of our knowledge, there does not exist any biomechanical data regarding mechanical properties of variable locking plate fixation compared to other types of fixation for proximal chevron osteotomy.

Therefore, the aim of the present study was to compare biomechanical properties of fixation of proximal chevron osteotomies with two different fixation methods.

Materials and methods

Specimens

A total of ten human first metatarsal bone matched pairs were obtained from donors. The donors consented in writing during

their lifetime to the use of their body for research and education and from these the data for this study was used. The study was approved by the Institutional Review Board (EK 1203/2013). All specimens were fresh frozen and exposed to room temperature only 24 hours before they underwent the testing. Donor age ranged from 64 to 90 years (mean, SD: 78.6, 8.4).

During a visual inspection of the bones to verify an intact bone structure, all specimens proved valid for the study. Each bone was stripped of all soft tissues, and all specimens were kept moist with saline irrigation throughout the surgical preparation.

All metatarsals were scanned using dual X-ray absorptiometry (DEXA) to quantify the bone mineral density (BMD).

Surgical procedure

A point is marked 20 mm distally to the articular surface of the base for the first metatarsal and at the midpoint in the dorsal plantar direction for the apex of the osteotomy. A proximally based chevron osteotomy is created at an angle of about 90 degrees using a microsagittal saw.

Complete release, plantarly and dorsally, is confirmed, and care is taken to not fracture either limb of the chevron osteotomy. The distal fragment is shifted laterally. It is translated 3 mm laterally and angulated 10 degrees laterally to simulate deformity correction.

For variable locking plate fixation the translated portion is secured temporarily with a 1.6 mm Kirschner wire from the dorsal aspect of the distal fragment aiming the plantar aspect of the base of the metatarsal. The prominent proximal fragment is trimmed flush with the distal fragment. Then an appropriately-sized titanium variable locking plate (2.7-mm variable angle, stable T arthrodesis plate; Königsee Implantate GmbH, Aschau, Germany) is applied to the medial cortex using the manufacturer's instrumentation and recommended technique (Fig. 1).

Since a biomechanical study has shown that plantar-to-dorsal screw orientation performs superior to dorsal-to-plantar orientation, this method was chosen for the present study [30].

Fig. 1 Variable locking plate fixation with 2.7-mm variable angle-stable T arthrodesis plate (Königsee Implantate GmbH, Aschau, Germany)

For screw fixation a guide wire for the cannulated 2.5-mm drill bit is inserted from plantar distal to the proximal dorsal aspect of the base of the first metatarsal. Then, the pilot hole is drilled perpendicularly to the osteotomy in lag fashion. After measuring for screw length, the proximal cortex is over-drilled using a 3.5-mm drill bit to create the gliding hole, and a 3.5-mm cannulated fully-threaded cortical screw (DepuySynthes, Salzburg, Austria) is inserted via the guide wire. Then, the K-wire is removed and specimens are prepared for mechanical testing [30] (Fig. 2).

Biomechanical testing

An experimental setup was designed in order to simulate post-operative in-vivo load conditions. Three conventional wood screws were inserted into the metatarsocuneiform articular surface of the osteotomized first metatarsal to allow more effective potting of the bone. The metatarsals were potted with their proximal aspects in Wood's metal in 40-mm diameter, custom built steel cups, which allow mounting in the 858 Mini

Fig. 2 Screw fixation for proximal chevron osteotomy with 3.5-mm cannulated fully-threaded cortical screw (DepuySynthes, Salzburg, Austria) from plantar to dorsal direction

Bionix® (MTS® Systems Corporation, Eden Prairie, MN, USA). Wood's metal was chosen as it is proven to be a superior moldable bonding material for biomechanical testing compared to polymethylmethacrylate (PMMA) [31], which is commonly used in similar biomechanical setups [20, 29]. The 858 Mini Bionix® is a servo hydraulic test frame, consisting of a loading frame (MTS® 858, Eden Prairie, MN, USA) with a stroke main actuator driven by a hydraulic pump unit (MTS® 505.11 silent flow, Eden Prairie, MN, USA) [32] (Fig. 3).

The potted specimens were rigidly fixed in an industrial vise with the metatarsal axis plantar flexed by 15° to simulate normal anatomic alignment [29, 33].

The measurement transducer for the force was integrated into the 858 Mini Bionix® testing system. The uncertainty in measurement for force of the system is 1 %. Load was recorded continuously at a sampling frequency of 60 Hz during testing.

An opto-electronic motion capture system, Smart-E (BTS Bioengineering, Milan, Italy) with four cameras with a sampling rate of 120 Hz was used to record the kinematics between the potted and the osteotomized segment of the metatarsal. Therefore 10-mm hemispherical markers were attached to the two segments using epoxy glue (Fig. 3).

Testing protocol

Each specimen was subject to repetitive plantar to dorsal loading from 0 to 31 N. The load was applied by a custom molded metal rod 14 mm in diameter, clamped into the hydraulic wedge grips of the loading frame. The load was applied at the center of the distal metatarsal head [20, 29, 32].

Load cycles 1, 10, 50, 100, 200, 300, 400, 500, 600, 700, 800, 900 and 1000 were linear ramps with a gradient of

Fig. 3 Biomechanical test setting. The potted specimen (1) was fixed into a vise (2). Light-reflecting markers were glued onto the distal part of the osteotomized and the potted proximal segments (3) for kinematic tracking. A metal rod (4) attached to the loading frame (5) was used for force transmission

7.75 N/s (corresponds a peak load of 31 N reached in four seconds). A compressive load of 31 N represents 1/3 of the mean load to failure observed by Trnka et al. [14], and it was chosen to achieve comparable data with similar studies [20, 29]. All of the intervening loads were cyclic loads performed at 0.5 Hz. One thousand load cycles were executed based on similar experimental setups and a realistic approximation of post-operative limb loading [20, 26, 29]. The load cycle 1000 was set to determine the failure load and mode with the same force gradient as described above.

Statistical analysis

Construct stiffness and the amount of distal fragment angulation at the peak load of 31 N were documented on the first, 10th, 50th, 100th, 200th, 300th, 400th, 500th, 600th, 700th, 800th, 900th, and 1000th load cycle. The slope of the latter one-quarter of the ascending load-displacement curve, a region that was consistently linear, is utilized to measure the stiffness in Newtons per millimeter of deflection of the distal metatarsal head. The screw and plate groups were compared in pair-wise fashion.

Paired, two-tailed Wilcoxon signed rank test was used to determine the significance of difference in dorsal angulation and bending stiffness between the experimental groups at each specified point in time during the repetitive loading, as well as the number of dorsal loads tolerated by each construct without exceeding 10 degrees of angulation.

Maximum load to construct failure and mean tolerated cycles until construct failure occurred were compared between the groups. Pearson product-moment correlation coefficient was calculated in order to investigate the relationship between failure mode and BMD.

Values of $p < 0.05$ were considered as statistically significant. Post-hoc power analysis revealed a statistical power of 92 % given the actual sample size for calculation of differences concerning bending stiffness.

Results

We observed statistically significant differences for all mechanical measurements in favor of the variable locking plate fixation group. All screw constructs failed after the first loading cycle. Four of ten plate constructs failed before completing 1000 load cycles in terms of construct failure or dorsal angulation of the distal fragment of more than 10° . Three constructs failed between the first and the tenth load cycle and another one between the 200th and the 300th load cycle.

Load to failure

The mean load tolerated until construct failure occurred was 16.7 N (SD 10.1) for the screw construct and 220.9 (SD 202.5) for the variable locking plate construct. The difference was statistically significant ($p=0.01$).

Bending stiffness

Mean bending stiffness of the screw construct was 2.1 (SD 1.5) N/mm for the screw construct and 33.0 (SD 27.4) N/mm for the locking plate construct. The difference was statistically significant ($p=0.012$). For the plate construct mean bending stiffness decreased between the first and the 1000th cycle from 33.0 (SD 27.4) to 25.7 (SD 27.5) N/mm. This decrease of 22.1 % was statistically significant ($p=0.021$).

Dorsal angulation

We found a statistically significant difference for dorsal angulation for all load cycles between the constructs. Mean dorsal angulation for the plate construct was 13.3 (SD 26.2) degrees at the first cycle, 11.0 (SD 11.5) at the tenth cycle, 13.7 (SD 14.2) at the 50th cycle, 14.4 (SD 14.9) at the 100th cycle and 19.6 (SD 21.0) at the 1000th cycle. There was an increase in dorsal angulation of 67.9 % between the first and the 1000th cycle. For the screw construct, dorsal angulation at the first cycle was 35.7 (SD 19.0) degrees (Fig. 5a, b). For locking plate constructs that did not fail mean dorsal angulation at the 1000th cycle was 0.9° (SD 0.3°). Due to failure of all constructs between the first and tenth cycle no dorsal angulation data was measured for other cycles.

Mode of failure

The most common failure mode for the screw construct was cut out of the head of the screw at the plantar cortical aspect ($n=4$) (Fig. 4a, b). In three specimens impaction of the dorsal cortical wing occurred with the screw staying in situ. In two specimens there occurred pull out of the threaded screw tip at the dorsal aspect of the proximal fragment. In the locking plate construct the most common failure mode was pull out of the proximal plantar locking screw with consecutive dorsal angulation of the distal fragment ($n=6$) (Fig. 4c, d). This was followed by medial deviation of the plate in three specimens and cut out of the proximal dorsal screw in one specimen Fig. 5.

Bone mineral density

The mean bone mineral density was 0.393 g/cm^2 (SD 0.14). There was no statistically significant difference between the groups. In the plate group BMD averaged 38.2 (SD 13.9) and

Fig. 4 a–d Typical mode of failure of variable locking plate (a,b) and screw construct (c,d), respectively

in the screw group it was 40.5 (SD 14.2). No statistically significant correlation was found for mechanical measurements and BMD for the plate construct. In contrast, there was a statistically significant correlation between BMD and maximum tolerated load until construct failure occurred for the screw construct ($r=0.640$, $p=0.406$).

Discussion

Correctional metatarsal osteotomies are the surgical treatment of choice for symptomatic hallux valgus deformity [13]. They can be performed at the distal, diaphyseal or proximal aspect of the first metatarsal.

Mathematical analysis revealed that distal metatarsal osteotomies (DMO) provide less correctional power than proximal metatarsal osteotomies (PMO). Therefore, DMO are preferred to correct mild to moderate hallux valgus deformities. Fixation in PMO is critical and complications due to high lever forces acting on the osteotomy site are common. The complications include shortening and dorsiflexion malunion leading to first ray insufficiency.

The proximal chevron osteotomy represents a proximal v-shaped metatarsal osteotomy with high correctional power and a relatively low complication rate compared to other proximal first metatarsal osteotomies [6].

Recent biomechanical and clinical studies pointed out the importance of rigid fixation of proximal metatarsal osteotomies and concluded that locking plate fixation might

Fig. 5 a, b Boxplots representing bending stiffness and dorsal angulation at the first load cycle of the two constructs

be recommended. However, to the best of our knowledge this is the first study that directly compares locking plate fixation to conventional screw fixation for proximal chevron osteotomy [6, 26, 32].

The major finding of the present study was that locking plate fixation revealed favorable results concerning biomechanical stability compared to single cancellous screw fixation for proximal chevron osteotomy. Bending stiffness and amount of dorsal angulation during cyclic loading conditions showed superior results for the locking plate construct compared to the screw construct. Additionally, we found statistically significant negative correlation between BMD and maximum load until construct failure occurs for screw fixation.

Limitations of this study include the fact that donor age is higher than what would be expected for most hallux valgus corrections. However, the donor age is similar to other biomechanical studies which focus on the comparison of surgical methods for hallux valgus reconstruction [34–36]. Also, due to the relatively high donor age, BMD shows lower values than in some comparable studies [20, 29]. Increased BMD might have influenced results in terms of lower number of failures, especially for the screw construct. However, since osteoporosis is increasing we do think that an important property of a modern fixation method should be sufficient fixation in bones with low BMD. Nevertheless, our data are laboratory results of a biomechanical setup and do not automatically correspond to clinical use.

Bending stiffness at the first load cycle significantly differed between the screw construct (2.1; SD 1.5 N/mm) and the locking plate construct (33.0; SD 27.4). Also, dorsal angulation at the first load cycle revealed statistically significant differences. There was a mean dorsal angulation for the plate construct of 13.3 (SD 26.2) degrees and for the screw construct of 35.7 (SD 19.0) degrees. These results indicate a higher stability of locking plate fixation compared to single screw fixation. Our results are comparable with those previously reported in a recent biomechanical study of Varen et al. They compared dorsal plate fixation and single screw fixation for proximal crescentic osteotomy under cyclic loading conditions and found the plate construct biomechanically more stable than the screw construct [32]. However, in the present study, four of ten plate constructs failed before completing 1000 load cycles in terms of construct failure or dorsal angulation of the distal fragment of more than 10° representing cut out of the plantar proximal screw as the most common failure mode. This is superior to the findings of Scott et al. They compared proximal chevron osteotomy with locking plate fixation to Ludloff osteotomy with screw fixation under cyclic loading conditions with the same testing protocol used in the present study. Of the ten locking plates tested six failed before completing the 1000th cycle. In accordance with the results of the present study most plate failures occurred before the 300th

cycle. The most common mode of failure was cut out of the plantar proximal screw which corresponds to the findings of the present study [29]. Hofstaetter et al. compared screw fixation for Ludloff osteotomy to plate fixation of proximal opening wedge osteotomies. They also found the same mode of failure for the plate constructs under cantilever bending forces. This distal migration of the plantar-proximal screw which allows for the excessive angulation seen in the present study is likely due to the fact that this plate is applied to the medial aspect of the osteotomy rather than to the tension side of the bone according to AO/ASIF principles [20].

The force applied in the present study that was recommended by Trnka et al. is relatively high considering the fact that peak pressure occurring in a modern forefoot relief shoe at the hallux region averages 16.8 N/cm² [14, 22]. However, we do not think that a lower amount of load would have affected the results in terms of biomechanical superiority of the variable locking plate construct.

A number of authors have studied the correlation between BMD and biomechanical stability of fixation methods of reconstructive hallux valgus procedures [20, 29, 32, 34, 35]. Some of them found correlations [20, 29, 32, 35] whereas others were not able to identify a significant relationship between BMD and fixation method [34]. In the present study, we found significant negative correlation between BMD and the maximum tolerated load until construct failure occurred. Therefore, BMD seems to play an important role in screw fixation. Screw fixation was also used in other studies in which correlations between BMD and biomechanical stability of the construct have been identified [20, 29, 32, 34]. In contrast, the results of the present study reveal no statistically significant correlation between BMD and biomechanical stability of variable locking plate fixation. These findings correspond to findings of other studies investigating plate fixation [29, 32, 35]. In conclusion, based on the results of the present study we consider variable locking plate fixation superior to single screw fixation concerning biomechanical stability for proximal chevron osteotomy. Despite the fact that previous studies indicated more favorable results in terms of bending stiffness and rotational stability for other proximal osteotomy constructs we recommend the chevron osteotomy with variable locking plate fixation since a recent meta analysis has shown that this procedure is associated with a low number of complications while providing a high amount of correction power. Special attention on fixation has been drawn to patients with low BMD due to osteoporosis. Plate fixation seems to provide sufficient fixation irrespective of BMD whereas stability of screw fixation seems to be related to BMD.

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