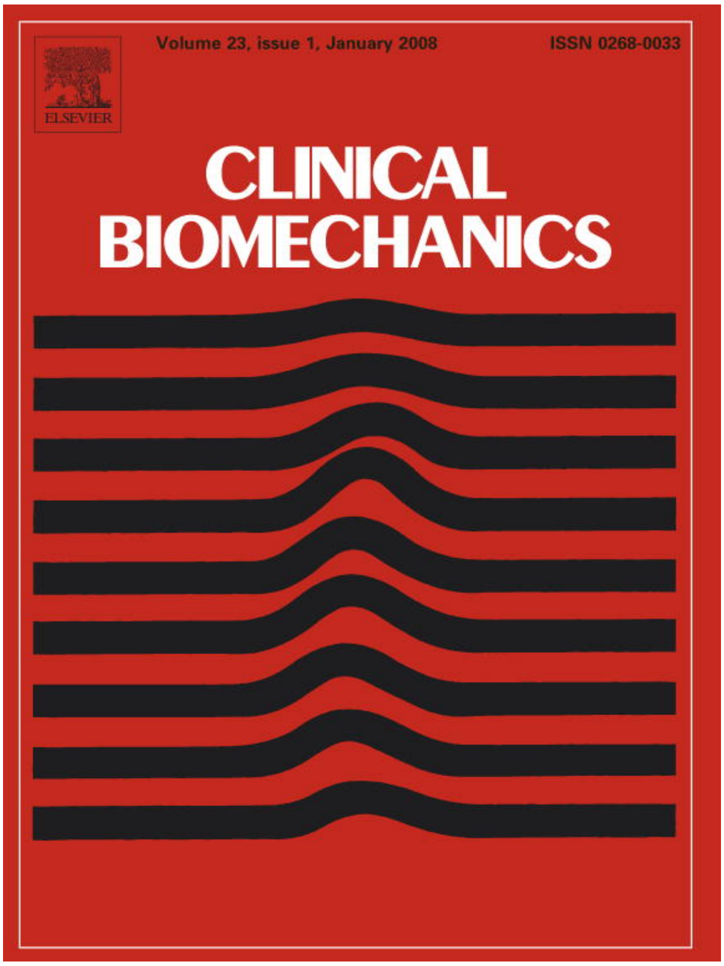
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Biomechanical comparison of screws and plates for hallux valgus opening-wedge and Ludloff osteotomies

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Abstract

Background. The optimal osteotomy type and fixation method for hallux valgus correction have not been defined. This study examined the mechanical properties of corrective opening-wedge and Ludloff oblique osteotomies under conditions approximating postoperative weight-bearing.

Methods. Twenty-nine pairs of fresh-frozen metatarsals were divided into three groups. In Group 1, headless screws were compared with standard cortical screws for Ludloff osteotomy fixation. In Groups 2 and 3, Ludloff osteotomies fixed with headless screws were compared with opening-wedge osteotomies fixed with non-locking and locking plates, respectively. Constructs underwent dorsally-directed cantilever loading for 1000 cycles.

Findings. No significant differences in angulation or stiffness were demonstrable in Group 1. In Group 2, Ludloff/headless screw construct stiffness exceeded non-locking plate construct stiffness. The mean angulation on the 1000th load cycle was greater for plates than for Ludloff/headless screws. In Group 3, locking plate construct stiffness and angulation did not differ from Ludloff/headless screws in early cyclic loading, but fixation failure of the locking plate constructs was common.

Interpretation. The results indicate that screw type for Ludloff fixation may be left to surgeon preference and that opening-wedge plates exhibit mechanical properties inferior to that of the Ludloff osteotomy under the tested conditions. Lateral cortex continuity and bone density remain important factors in the performance of opening-wedge osteotomies.

Keywords: Screw; Plate; Stiffness; Angulation; Hallux valgus; Foot

1. Introduction

Over one hundred first metatarsal osteotomy procedures have been described for the correction of symptomatic hallux valgus deformities (Helal et al., 1974). In cases in which the intermetatarsal angle exceeds 15°, a proximal osteotomy is indicated (Jahss et al., 1985; Kummer, 1989). The Ludloff osteotomy, an oblique osteotomy typically fixed with two screws, is a commonly used procedure, but it is accompanied by a risk of postoperative dorsal angulation due to failure of the fixation. Clinical reports have noted dorsal angulation of the first metatarsal after various proximal osteotomies in up to 28% of cases, with subsequent transfer metatarsalgia (Easley et al., 1996; Mann et al., 1992; Zettl et al., 2000). Although this complication may occur as a result of intraoperative technical error, it can also result from patient non-compliance or early weight-bearing on an unstable osteotomy (Acevedo et al., 2002; Pearson et al., 1991). Therefore, the post-surgical stability

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of the first ray is critical for successful hallux valgus correction (Schutz and Sudkamp, 2003; Trnka et al., 2000).

First metatarsal osteotomy fixation must offer high bending stiffness and low interfragment motion in order to promote osteosynthesis (Lienau et al., 2005; Seebeck et al., 2005). A number of studies have been published in which the bending stiffness of fixed first metatarsal osteotomies has been evaluated, but they employed single-load catastrophic failure testing (Jones et al., 2005; Stamatis et al., 2003; Trnka et al., 2000). While fixation failure subsequent to a single high-magnitude load may occasionally occur clinically, fatigue failure caused by repeated loading and unloading is the most common mode of failure. Acevedo et al. (2002) determined the fatigue endurance of the proximal crescentic, proximal chevron, Ludloff, scarf, and Mau osteotomies in plastic foam surrogate metatarsals, and found that the proximal chevron and Mau osteotomies withstood the most load cycles. They subsequently compared the proximal chevron and Ludloff osteotomies in matched pairs of cadaver metatarsals and were unable to demonstrate a difference in fatigue resistance.

Biomechanical and mathematical investigations have indicated that the Ludloff osteotomy provides a superior combination of fixation integrity and ability to correct severe deformities (Nyska et al., 2002; Trnka et al., 2000). Clinical reports have also been positive, with low incidences of malunion and transfer metatarsalgia (Chiodo et al., 2004; Cisar et al., 1983; Saxena and McCammon, 1997). 3.0 mm cortical screws are commonly used to fix the Ludloff osteotomy, and a headless, cannulated, dual-thread screw has recently become an option.

An alternative approach to hallux valgus correction utilizes a medial opening-wedge osteotomy created at the base of the metatarsal. Fixation of these osteotomies has been problematic in the past, with failures resulting in loss of the initial correction (Amarnek et al., 1986). To address this problem, opening-wedge plates have recently been designed specifically for use on the first metatarsal. These titanium plates span a corrective medial wedge osteotomy and incorporate a 2–5 mm spacer that is positioned such that it mechanically prevents closing of the open end of osteotomy during subsequent healing. The original length of the metatarsal is thereby preserved or even slightly increased.

This study had two goals. The first was to identify any performance differences between conventional cortical screws and headless, dual-thread screws for fixation of Ludloff osteotomies. The second goal was to subsequently determine whether opening-wedge osteotomies fixed with the two commercially-available opening-wedge plates, one of which of uses locking screws and the other which uses non-locking screws, exhibit mechanical integrity superior to that of the Ludloff osteotomy fixed with the screw type deemed more advantageous. Emphasis was placed on the ability of the construct to resist dorsal angulation during repetitive loading. This information will provide the orthopaedic surgeon with quantitative data that may be referred to in selecting an optimal fixation method for hallux valgus correction.

2. Methods

2.1. Experimental groups

Twenty-nine matched pairs of fresh frozen cadaveric first metatarsals were used for this study. All tested metatarsals were visually verified to be normal in appearance. The metatarsal pairs were randomly divided into three groups, as follows: in the first group ($n = 9$ pairs), metatarsals in which a Ludloff osteotomy was fixed with two Synthes 3.0 mm self-tapping cortical screws (Synthes USA, Monument, CO, USA) were compared with contralateral metatarsals in which the same osteotomy was fixed with two DePuy Fusion and Reconstruction System (FRS) screws (DePuy, Inc., Warsaw, IN, USA). The latter are cannulated screws that have cancellous leading threads with a diameter of 3 mm and cortical trailing threads with a smaller pitch and a diameter of 4 mm. Donor age for this subgroup ranged from 49 to 68, with a mean age of 60. Five donors were male and four female. The results of this portion of the study were used to select a Ludloff/screw construct for use as a benchmark in subsequent comparisons with the two plate constructs.

In the second group ($n = 10$ pairs), one metatarsal from each pair received a Ludloff osteotomy fixed with FRS screws as described above. Opening-wedge osteotomies were created in each of the contralateral metatarsals and fixed with an Arthrex Low Profile Plate and Screw System opening-wedge plate with a 3 mm block (Arthrex, Inc., Naples, FL, USA). These plates are "L" shaped, 0.5 mm thick, and are affixed with four low-profile 2.2 mm-diameter cortical screws. Donor age ranged from 32 to 61, with a mean age of 50. Seven donors were male and three female.

In the third group ($n = 10$ pairs), one metatarsal from each pair received a Ludloff osteotomy fixed with FRS screws as described above. Opening wedge osteotomies were created in each of the contralateral metatarsals and fixed with a Darco BOW opening-wedge plate with a 3 mm block (Darco (Europe) GmbH, Raisting, Germany, Europe). These plates are "H" shaped, 1.0 mm thick, and are affixed with four 2.7 mm-diameter cortical screws that lock to the plate with threads. Donor age ranged from 50 to 84, with a mean age of 67. Three donors were male and seven female.

2.2. Specimen preparation and handling

Each first metatarsal was stripped of all soft tissue. Each bone was scanned using dual X-ray absorbitometry (DEXA) to quantify the bone mineral density, and then frozen at −20 °C until use. All specimens were kept moist with saline irrigation during surgical preparation and mechanical testing to prevent desiccation.

2.3. Surgical procedures

In metatarsals undergoing the Ludloff procedure, the osteotomy was created using an oscillating saw with a 0.4 mm-kerf blade. The osteotomy began dorsally at the level of the metatarsocuneiform joint and progressed distally, ending proximal to the sesamoid apparatus. The osteotomy was stopped short of completion, and the proximal fixation screw was inserted perpendicular to the plane of the osteotomy. The osteotomy was then completed, the distal fragment was rotated approximately 10° medially about the proximal screw, and the distal screw was inserted (Fig. 1a). The proximal screw was inserted in a dorsal-to-plantar direction, and the distal screw was inserted plantar-to dorsal. In the case of the FRS screws, the screws were inserted with bicortical thread engagement. The screws with heads were inserted bicortically in lag fashion with thread engagement only in the far cortex.

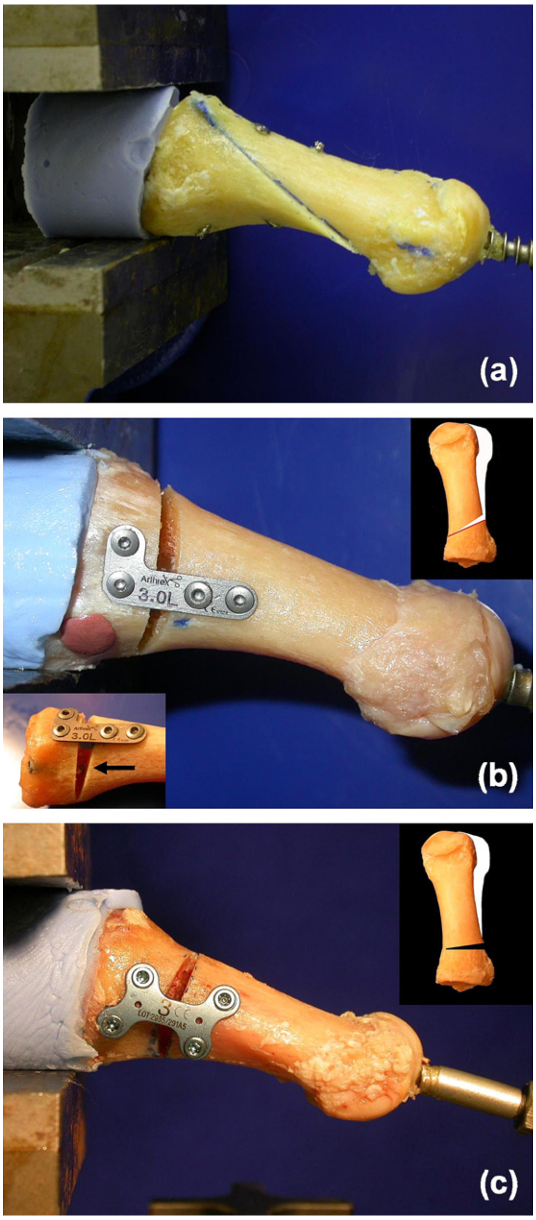

Fig. 1. (a) Ludloff osteotomy of first metatarsal fixed with two DePuy FRS screws. (b) Opening wedge osteotomy fixed with an Arthrex Low Profile Plate and Screw System opening-wedge plate incorporating a 3 mm block. The arrow indicates the location of the partially visible augmenting cortical screw. (c) Opening-wedge osteotomy fixed with a Darco BOW opening-wedge plate incorporating a 3 mm block.

In metatarsals receiving the Arthrex Low Profile Plate, a slightly oblique transverse corrective opening wedge osteotomy was performed 12 mm distal to the metatarsocuneiform joint using an oscillating saw with a 0.4 mm-kerf blade. The osteotomy was started on the medial side and stopped 1–2 mm short of full penetration of the lateral cortex in order to leave a ''hinge''. The osteotomy was opened enough to produce a 3 mm gap medially, the plate was applied, and the screws inserted bicortically (Fig. 1b). The osteotomy fixation was augmented by placing an additional 2.3 mm cortical screw at an angle from proximal-medial to distal-plantar across the osteotomy.

In metatarsals receiving the Darco BOW opening wedge plate, a transverse corrective opening wedge osteotomy was performed 12 mm distal to the metatarsocuneiform joint using an oscillating saw with a 0.4 mm-kerf blade. As in metatarsals that received the Arthrex plate, the osteotomy was started on the medial side and stopped 1–2 mm short of full penetration of the lateral cortex. The osteotomy was opened, the plate applied, and the screws inserted bicortically without a fifth augmenting screw (Fig. 1c).

2.4. Mechanical testing

The base of each metatarsal was rigidly embedded in a cylinder of polymethylmethacrylate cement after measuring the distance from articular surface of the base to the center of the head. Before embedding the proximal fragment, six small sheet metal screws were inserted into the metatarsocuneiform articular surface, such that their shafts projected proximally, to ensure solid embedding. A distally-projecting rod fabricated from a modified 6.5 mm cancellous lag screw was inserted into the head and distal shaft, coaxial with the shaft of the metatarsal. The embedded proximal end of the metatarsal was then clamped in a vise with the axis of the bone angled plantarward 15°. A rod-end bearing attached to the load cell of a computer-controlled Instron 1321 servohydraulic materials testing machine was slipped over the distally projecting rod and positioned 5 cm distal to the center of the head. A Lucas AccuStar electronic clinometer (Lucas Control Systems, Hampton, VA, USA) was fixed to the end of the projecting rod (Fig. 2).

Each metatarsal was subsequently cyclically loaded 1000 times, or until gross failure, in cantilever fashion, while monitoring load, displacement, and dorsal angulation. Failure was defined as interfragment angulation in excess of ten degrees. Loading was applied in a plantar-to-dorsal direction, with the effective load varying from 0 N to 31 N at the center of the metatarsal head. The 31 N effective load was achieved by reducing the applied load according to the

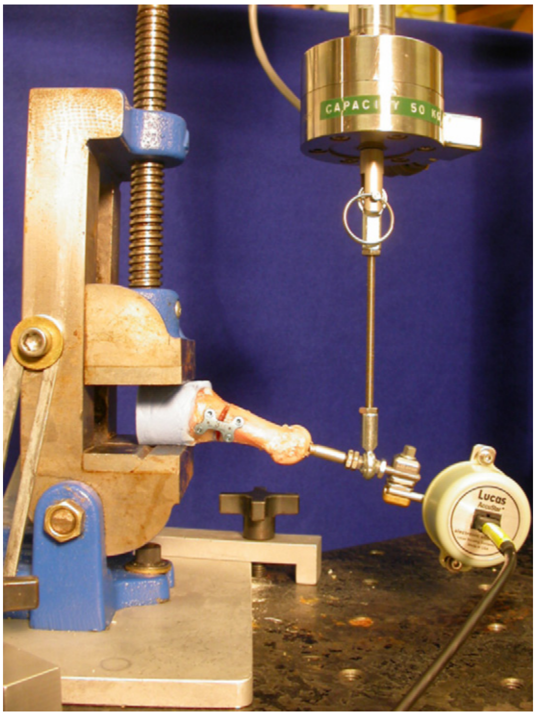

Fig. 2. First metatarsal mounted in testing machine. Load was cyclically applied in plantar-to-dorsal direction while monitoring load, displacement, and angulation.

ratio of the distance from the base of the metatarsal to the center of the head and the distance from the base to the load application point. This peak load magnitude is 1/3 of the mean Ludloff osteotomy fixation failure load determined by Trnka et al. (2000), and was selected to substantially challenge the construct without prematurely damaging it during the cyclic loading. The number of load cycles was chosen based on the loading rate for a physiologically normal lower limb, which is approximately 5000 cycles per day. One thousand cycles per day was felt to realistically approximate postoperative limb loading. Load cycles 1, 10, 50, 100, 200, 300, 400, 500, 600, 700, 800, 900, and 1000 were linear ramp loads applied at 7.75 N/s, and all other load cycles were sinusoidal at 0.5 Hz. The cycling was performed with the testing machine under load control with the gain set to accurately achieve the maximum and minimum loads. The specified load cycles were programmed as linear ramps to readily distinguish them from the other load cycles when analyzing the data and to facilitate stiffness calculation.

2.5. Data analysis

Construct stiffness and the amount of interfragment angulation were calculated on the 1st, 10th, 50th, 100th, 200th, 300th, 400th, 500th, 600th, 700th, 800th, 900th and 1000th load cycles. Stiffness was derived from the slope of the latter one-quarter of the ascending load–displacement curve, a region that was consistently linear, and expressed as newtons per millimeter of deflection of the metatarsal head. The mechanical properties of the Ludloff/cortical screw construct and the two opening-wedge plate constructs were compared in pair-wise fashion to the respective contralateral Ludloff/FRS screw constructs. The mode of failure was documented in cases in which fixation failure occurred during cyclic loading.

Statistical significance was set at the 95% confidence level. Paired, two-tailed Wilcoxon signed rank tests were used to determine the significance of differences in the number of load cycles withstood before failure, dorsal angulation at each cyclic load interval, and construct stiffness at each cyclic load interval. Because experimental group sizes were limited by specimen cost and availability, post hoc statistical power calculations were performed and reported where pertinent.

3. Results

3.1. Dorsal angulation

No differences in dorsal angulation during cyclic loading were identifiable between the matched paired constructs compared in Group 1 (Table 1). One of nine Ludloff/3.0 mm cortical screw constructs failed (that is, exceeded 10° of angulation) before 1000 cycles, between the 10th and 50th cycles. Two of nine Ludloff/FRS screw constructs failed before completion of 1000 load cycles, one between the 200th and 300th cycles, and the other between the 700th and 800th cycles. Neither of the latter was contralateral to the construct that failed in the Ludloff/3.0 mm cortical screw group. No difference in the average number of load cycles tolerated was identifiable between treatment subgroups (890 for 3.0 mm cortical, 878 for FRS). For constructs that did not fail, the mean angulation on the 1000th load cycle was 2.4° (range 0.5–5.7) for the cortical screws ($n = 8$) and 2.8° (range 1.2–5.0) for the FRS screws ($n = 7$). The mean change in angulation under load between the 1st and 1000th cycles was 0.6° and 0.7° for the cortical screws and FRS screws, respectively.

In Group 2, one Arthrex plate construct failed during cyclic loading, between cycles 600 and 700. All of the Ludloff/FRS screw constructs completed 1000 load cycles without exceeding 10° of dorsal angulation. No difference was demonstrable in the number of load cycles tolerated. In metatarsals in which fixation did not fail, the mean angulation on the 1000th load cycle was 3.9° (range 1.4–9.8) for the plates ($n = 9$) and 1.6° (range 0.8–3.2) for the FRS screws ($n = 10$) (Table 1). Angulation of the plated constructs exceeded that of the Ludloff/FRS constructs at load cycles 50 through 1000 ($P = 0.002$–0.019).

In Group 3, six of the 10 Darco BOW plate constructs failed during cyclic loading, four between the 10th and 50th, one between the 100th and 200th, and one between the 300th and 400th cycles. Two of ten Ludloff/FRS screw constructs failed before completion of 1000 load cycles, one between the 400th and 500th, and one between the 500th and 600th cycles. Only one of these was the contralateral

Table 1
Interfragment angulation

Fixation method	Mean angulation on 1st load cycle (°)	Mean angulation on 1000th load cycle (°)	Mean angulation increase between 1st and 1000th load cycles (°)
Group 1			
3.0 cortical	2.2 (1.7), $n = 9$	2.4 (1.6), $n = 8$	0.6 (0.6)
FRS	2.3 (0.8), $n = 9$	2.8 (1.3), $n = 7$	0.7 (0.7)
Group 2			
Arthrex plate	1.8 (0.8), $n = 10$	3.9 (3.0), $n = 9$	2.1 (2.4)
FRS	1.4 (0.5), $n = 10$	1.6 (0.7), $n = 10$	0.2 (0.2)
Group 3			
BOW plate	2.7 (2.2), $n = 10$	2.4 (2.5), $n = 4$	0.9 (1.3)
FRS	1.9 (0.4), $n = 10$	2.2 (0.6), $n = 8$	0.4 (0.2)

Numbers in parentheses are standard deviations.

to a failed Darco BOW plate construct. No difference in angulation between the two types of fixation was demonstrable on the 1st and 10th load cycles, which were the only measurement points during cyclic loading at which none of the 10 pairs of metatarsal constructs had failed. The small number of metatarsals fixed with the Darco BOW plate that withstood more than 10 load cycles made legitimate statistical comparisons of interfragment angulation beyond the 10th cycle impossible. Only three pairs of metatarsal constructs out of the initial 10 pairs tolerated all 1000 of the load cycles. Post hoc power calculation for the difference in angulation at load cycle 50 and higher indicated that achieving a power of 0.80 for these comparisons would have required group sizes several times larger than possible with the specimens available to us. However, the number of load cycles tolerated by the Ludloff constructs before exceeding 10° of dorsal angulation was significantly greater than ($P = 0.047$).

3.2. Bending stiffness

There was no significant difference in bending stiffness between metatarsals fixed with FRS or 3.0 cortical screws at any point during the cyclic loading. In Group 1, bending stiffness averaged 20.6 N/mm (range 8.9–39.0) N/mm of head deflection at the 1000th cycle for Ludloff osteotomies fixed with cortical screws and 16.6 (range 6.4–37.5) N/mm for those fixed with FRS screws (Table 2). The change in stiffness between the 1st and 1000th load cycles for constructs that withstood all 1000 loads was minimal for both of the Ludloff osteotomy constructs. Because no performance differences could be identified between the two types of screws used in Group 1, the FRS screw was selected as a benchmark for subsequent comparison with opening wedge plate constructs on the basis of the cosmetic advantage afforded by the headless design.

In Group 2, Ludloff/FRS screw construct bending stiffness exceeded Arthrex plate construct stiffness at all measurement points between the 10th and 1000th load cycles ($P = 0.006$–0.020). The mean stiffness of the metatarsals fixed with the Arthrex plate decreased as cyclic loading progressed, a phenomenon that was seen only in metatarsals fixed with this plate. The mean bending stiffness decrease in the Arthrex plate constructs between the first and last cycles was 15.1%, and the stiffness compared with that measured on the 1000th cycle was significantly greater at cycles 10, 50, 100, 200, 300, 400, and 500 ($P = 0.004$–0.012).

In Group 3, Darco BOW plate construct stiffness did not differ from Ludloff/FRS values early in the cyclic loading. Beyond the 10th load cycle, an inadequate number of the plate constructs survived to allow statistical comparison. As with the angulation results, post hoc power calculation for the stiffness difference at load cycles 50 and

Table 2
Bending stiffness

Fixation method	Mean stiffness on 1st load cycle (N/mm)	Mean stiffness on 1000th load cycle (N/mm)	Mean % change in stiffness between 1st and 1000th load cycles
Group 1			
3.0 cortical	18.6 (11.1), $n = 9$	20.6 (11.1), $n = 8$	0.5 (10.2) (increase)
FRS	14.6 (7.9), $n = 9$	16.6 (10.4), $n = 7$	0.1 (14.8) (increase)
Group 2			
Arthrex plate	17.1 (7.4), $n = 10$	15.6 (7.7), $n = 9$	15.1 (25.0) (decrease)
FRS	24.1 (9.7), $n = 10$	28.0 (12.9), $n = 10$	14.7 (14.4) (increase)
Group 3			
BOW plate	19.8 (13.7), $n = 10$	32.6 (16.2), $n = 4$	17.7 (3.7) (increase)
FRS	16.3 (6.1), $n = 10$	19.4 (5.9), $n = 8$	15.5 (14.3) (increase)

Numbers in parentheses are standard deviations.

higher indicated that group sizes several times larger than utilized would be necessary for adequate statistical power.

3.3. Failure modes

Failure of the Ludloff osteotomy constructs typically involved loss of thread engagement at the distal screw and fracture of the dorsal cortex adjacent to the proximal screw as the distal fragment pivoted dorsally (Fig. 3a). Failure of the plate-fixed opening-wedge osteotomies involved fracture of the 1–2 mm thick lateral cortex "hinge" at the apex of the osteotomy. This was accompanied by distal migration of the proximal plantar screw through the adjacent bone, which allowed interfragment angulation (Figs. 3b and c). In metatarsals fixed with Arthrex plates, the augmenting fifth screw concurrently lost thread purchase. The Arthrex plates typically retained some resistance to angulation as cyclic loading progressed, but constructs fixed with Darco plates tended to lose angulation resistance more rapidly.

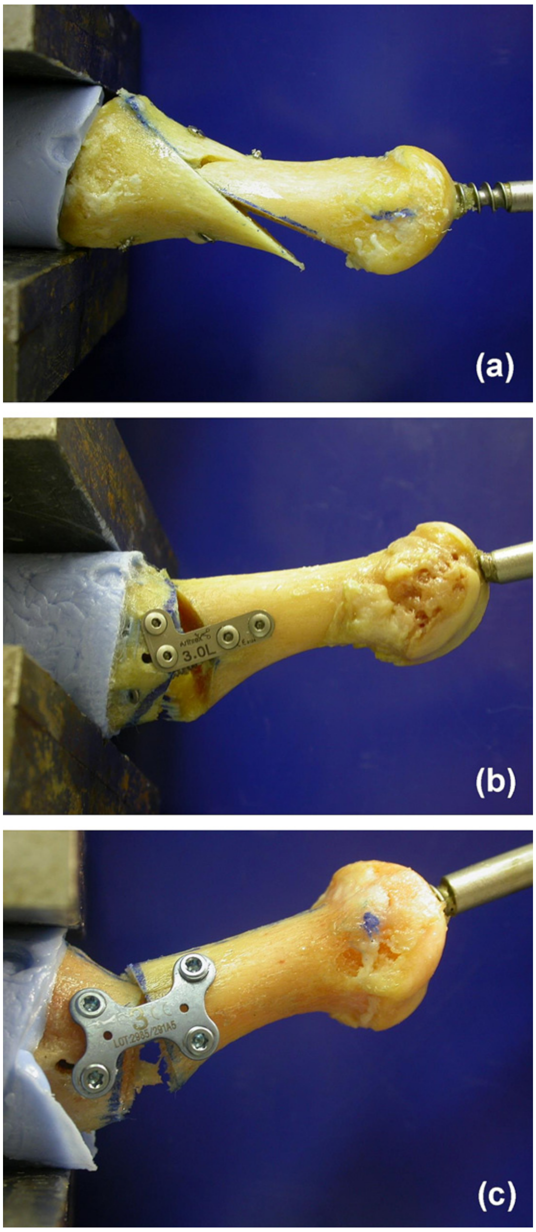

Fig. 3. (a) Typical failure mode of Ludloff osteotomy fixed with 3.0 cortical screws. Dorsal surface of bone is facing up. Constructs fixed with FRS screws failed in a similar manner. (b) Typical Arthrex plate fixation failure mode. The lateral cortex has fractured, allowing dorsal angulation of the distal fragment. The proximal plantar screw migrated laterally through the adjacent bone and the augmenting 5th screw pulled out. (c) Typical Darco plate fixation failure mode. The lateral cortex has fractured, allowing dorsal angulation of the distal fragment as the proximal plantar screw migrated laterally through bone.

Table 3
Correlation between bone mineral density and bending stiffness and dorsal angulation on 10th load cycle

Fixation method	Correlation coefficient, *r*	
	Angulation at cycle 10	Stiffness at cycle 10
Group 1		
3.0 Cortical	+0.13	+0.28
FRS	−0.29	+0.32
Group 2		
Arthrex plate	−0.57	+0.47
FRS	−0.85	+0.88
Group 3		
BOW plate	−0.32	+0.19
FRS	−0.66	+0.70

3.4. Bone mineral density

The mean bone mineral density was 0.52 (range 0.33–0.69) for Group 1 (3.0 cortical vs. FRS), 0.55 (range 0.38–0.73) for Group 2 (Arthrex plate vs. FRS), and 0.40 (range 0.29–0.55) for Group 3 (Darco plate vs. FRS). Pearson product–moment correlation coefficients relating bending stiffness and dorsal angulation to bone mineral density were calculated for the 10th load cycle, which was the highest number of cycles tolerated by all tested metatarsals (Table 3). There was a mild-to-moderate correlation between bone density and both measured parameters in the metatarsals that were fixed with the Arthrex plate and in the Group 2 and 3 metatarsals fixed with FRS screws. Higher bone density was associated with lower angulation and higher stiffness in these cases.

4. Discussion

One goal of the study presented herein was to determine whether cosmetically advantageous headless screws perform as well as conventional headed screws for Ludloff osteotomy fixation. The results indicate that the type of fixation screw may be left to surgeon preference, as there was no evidence that the performance of the conventional lag screws differed from that of the headless, dual-thread screws for this application.

While the Ludloff osteotomy fixed with two screws is generally regarded as an effective method of hallux valgus correction, opening-wedge plates offer an alternative that may better preserve bone length, and they mechanically block closing of the osteotomy. The second goal of this study was to determine whether fixation using either of the currently available plates designed for this application performs in a manner superior to a standard Ludloff osteotomy under the tested conditions. It was found that fracture of the relatively weak lateral cortical bone "hinge" results in loading of the medially-located plate and screw constructs in a plane in which it has limited capacity to resist dorsal angulation, despite the presence of the "block" designed to keep the osteotomy from closing.

Because the study presented herein is based on a necessarily simplified and standardized cadaveric model, some limitations should be kept in mind when interpreting the results. First, the model simulates only the immediate postoperative condition, and therefore cannot assess the influence of the bone healing process. However, it has been shown biomechanically and histologically that different fixation stiffnesses result in different degrees of inter-fragment movement, leading to different healing rates (Seebeck et al., 2005). Larger interfragmentary movements result in slower callus mineralization and fracture healing. Therefore, because of the established correlation between the adequacy of the fixation and the healing rate, the quantification of initial construct stiffness and ability to maintain mechanical integrity during subsequent cyclic loading may be assumed to have substantial value in predicting the outcome of the surgery. Although fixation failure may occur differently in vivo, the commonly used clinical failure criterion of excessive dorsal angulation is the same failure criterion used in this experimental study.

A second potential limitation is that the experimentally-applied cyclic load magnitudes may not correspond to those experienced by the first metatarsal clinically. Rehabilitation after hallux valgus correction involves repeated loading and unloading of the metatarsals as the patient bears weight. This repetitive loading can cause failure, even though each individual load creates stresses that are below the ultimate strength of the fixation. Loading of the first metatarsals in this study was designed to grossly simulate in vivo loading and to provoke dorsal angulation, a clinical complication that signifies failure of the hallux valgus corrective surgery if excessive. The peak applied load of 31 N was chosen based on a contemporary report of forces found to induce fixation failure in cadaver metatarsals with hallux valgus corrective surgeries (Trnka et al., 2000). This load was not adjusted for donor body mass or bone size. The selected load was applied in a cyclical manner to better replicate postoperative weight-bearing, and accomplished the goal of identifying weaker constructs while allowing nondestructive completion of 1000 load cycles by those constructs with relatively superior integrity.

Acevedo et al. (2002) performed a biomechanical study in which cyclic bending loads were applied to common osteotomies, including the Ludloff, in plastic surrogate and cadaver first metatarsals. They reported that proximal chevron and Mau osteotomies withstood the most load cycles in the surrogate bones. Comparing proximal chevron and Ludloff osteotomies in matched pairs of cadaver metatarsals, they found no difference in fatigue resistance. The authors did not state the load applied to the metatarsals, only that it was based on 280 kPa pressure, which they further stated is 90% of the average peak pressure reported in the literature. They did not report the actual failure modes, stating only that the failure criteria were bony fracture, screw pull-out, or gapping exceeding 2 mm. They did not quantify angulation.

Jones et al. (2005) measured dorsal displacement during application of a cyclic load of 27 N to plastic foam first metatarsal models with a crescentic osteotomy fixed with either a 3.5 mm cortical screw and 0.062-in. Kirschner wire or an experimental dorsolateral plate. They showed no difference in dorsal displacement between groups, and greater bending stiffness for the plated constructs. Failure of the plated surrogate metatarsals was consistently accompanied by fracture of the bone between the screws and the osteotomy site, but the fracture properties of the plastic foam may differ considerably from those of real bone.

Observation of the failure modes of the Ludloff osteotomies in the present study showed a consistent pattern of loss of thread engagement of the distal screw and fracture about the head of the proximal fixation screw as the distal fragment pivoted dorsally. Plated opening-wedge osteotomies consistently failed by distal migration of the proximal plantar screw concomitant with fracture of the lateral cortical bone "hinge". The finding that metatarsals fixed with Darco BOW plates tended to fail more abruptly compared to those fixed with Arthrex plates may be related to the rigid, threaded connection between the screws and the plate. In contrast, the Arthrex plate's screws are free to pivot within the holes in the plate and their shafts have greater freedom to angulate as the adjacent bone yields from excessive loading. This, coupled with the thin, relatively flexible design of the Arthrex plate, may have been responsible for the more gradual failure. Unlike all of the other tested constructs, the stiffness of those fixed with the Arthrex plate decreased as cycling progressed.

There was inequality in the average bone mineral density between the experimental groups in the present study as a result of randomly selecting the metatarsal pairs assigned to each, but exclusive use of pair-wise comparisons in this study reduced the influence of this variable. It has previously been reported that bone mineral density may influence fixation integrity in hallux valgus surgery (Acevedo et al., 2002). There does appear to be moderate correlation between density and fixation integrity, particularly when FRS screws are used. However, the association between bone density and fixation integrity was not consistent. Irrespective of bone quality, it is apparent that variables such as the osteotomy angle and the locations, angles, and spacing of the screws used in Ludloff osteotomies all affect the durability of the fixation (Nyska et al., 2002; Stamatis et al., 2003).

Similar variables no doubt influence opening-wedge plate fixation, particularly the thickness of the lateral cortical "hinge" and the degree to which the bone at the "hinge" vertex fractures intraoperatively as the osteotomy is opened. The latter variable was not quantified in the present study. The "hinge" is used primarily as a means of maintaining the rotational alignment of the distal fragment as the osteotomy is opened, and heretofore its thickness has not been viewed as critical. To date there are only two clinical reports about the use of opening wedge plates. Siekmann (2003) did not address the hinge issue in his paper, whereas Willauschus et al. (2006) did discuss the importance of the lateral cortex. In four of 36 patients in their series the lateral cortex fractured, leading to loss of correction in three cases. In light of the observed mode of failure of the opening-wedge plates, it appears that the integrity of the lateral "hinge" needs to receive greater emphasis if the potential of the plates is to be realized.

We selected the Ludloff osteotomy as a benchmark for comparison with the opening-wedge plates because it has consistently performed favorably in both biomechanical and clinical studies (Jones et al., 2005; Stamatis et al., 2003; Trnka et al., 2000). Further, the procedure is relatively straightforward technically, as it involves a single straight osteotomy and control of the distal fragment's orientation is maintained throughout. The resulting broad bony apposition and double screw compression facilitate mechanical stability and rapid union (Chiodo et al., 2004). In a three-dimensional geometric analysis, the Ludloff osteotomy was shown to be capable of greater angular correction compared to other common osteotomies, as well as more accurate attainment of the desired degree of correction (Nyska et al., 2002).

5. Conclusion

In conclusion, our biomechanical data suggest that an opening-wedge osteotomy fixed with either of the tested plates is likely to have less integrity than that afforded by the Ludloff osteotomy. The latter may be performed with headed or headless screws with equal effectiveness. However, there are variables such as bone quality that can affect the result of either procedure. In the case of the plates, the effect of variation in the quality of the lateral cortical "hinge" requires further investigation.

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