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The influence of patient age and bone mineral density on osteotomy fixation stability after hallux valgus surgery: A biomechanical study

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ABSTRACT

Background: Oblique osteotomies of the first metatarsal are common surgical treatments for moderate to severe hallux valgus deformity. Osteotomy fixation integrity is important to minimize interfragment motion and maintain correction during healing, and our clinical observations suggest that patient age and bone quality affect fixation stability and ultimately the clinical outcome. Accordingly, this study correlated these patient factors with key mechanical measures of osteotomy angulation resistance in a cadaver hallux valgus correction model.
Methods: Standard Ludloff osteotomies were created in 31 fresh-frozen first metatarsals and fixed with two cannulated, dual-pitch headless screws. Each specimen underwent 1000 plantar-to-dorsal bending loads while monitoring bending stiffness and distal fragment dorsal angulation. Donor age and bone mineral density were then correlated with each mechanical measure at selected cycling increments.
Findings: We found significant positive correlation between bone mineral density and osteotomy fixation stiffness for all evaluated load cycles. Moderate negative correlation between bone density and angulation was identified, significant for load cycle 500. There was a weak, nonsignificant negative correlation between donor age and osteotomy bending stiffness, with r ranging from -0.134 to -0.243 between the first and 1000th loads. Little correlation was demonstrable between age and angulation.
Interpretation: Because low bone density correlates with decreased osteotomy site stiffness and increased angulation under load, patient compliance and protected weight bearing in the early postoperative phase are particularly important if bone mineral density is exceptionally low. Correspondingly, patients with especially high bone mineral density may be considered candidates for earlier weight bearing and active physical therapy.

1. Introduction

Realignment osteotomies of the first metatarsal are commonly performed for hallux valgus correction, and more than 100 procedures have been described (Helal et al., 1974). Moderate to severe symptomatic hallux valgus associated with a first intermetatarsal angle (IMA) exceeding 15° is corrected typically with a proximal or diaphyseal first metatarsal osteotomy and distal soft tissue procedure when non-operative treatment fails (Chiodo et al., 2004; Jahss et al., 1985). Proximal crescentic, proximal chevron, and modified Ludloff osteotomies are used commonly, and the effectiveness of these corrective approaches has been established by a number of studies (Chiodo et al., 2004; Easley et al., 1996; Gallentine et al., 2007; Mann et al., 1992; Sammarco and Russo-Alesi, 1998; Trnka et al., 2008). Ludloff first described the osteotomy bearing his name in 1918 as an oblique osteotomy from the dorsal–proximal to plantar–distal aspects of the first metatarsal, performed without internal fixation (Ludloff, 1918). Cisar et al. (1983) reported using the technique with internal fixation in 1983, and the procedure modified with internal fixation gained further attention in 1997 when Myerson (1997) and Saxena and McCammon (1997) reported favorable results.

Trnka et al. (2008) evaluated the modified Ludloff osteotomy in a prospective study of 111 cases at intermediate-term follow-up. They reported osseous callus formation at the osteotomy site 6 weeks postoperatively in 18 cases (16%) and considered the callus formation to be indicative of osteotomy site motion during healing. In an effort to identify factors influencing clinical outcome, they arbitrarily divided patients into those older and younger than 60 years of age. They noted that the younger patients had a significantly higher mean total American Orthopaedic Foot and Ankle Society (AOFAS) forefoot–metatarsophalangeal–interphalangeal outcome score than did patients over 60 years of age. Further, the average age of patients with abnormal bony callus formation (63 years) was significantly higher than that of patients without callus formation (54 years). They did not demonstrate

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a significant difference in hallux valgus correction achieved between the age groups, but the mean intermetatarsal angle was significantly greater in the individuals with excessive callus. The authors speculated that osteopenic bone resulted in less rigid osteotomy site fixation in older individuals, but did not explore that premise further.

In another large series, Chiodo et al. (2004) documented excellent correction at 30 months follow-up in 70 cases but noted delayed union and callus formation in three of the cases. They did not investigate the relationship between outcome and patient age or bone density. Robinson et al. (2009) reported three cases (5%) of delayed union of the Ludloff osteotomy in 57 patients, two of which healed with dorsiflexion malunion. The relationship between outcome and patient characteristics was not reported.

It is recognized that secure fixation is a prerequisite for expeditious bone healing (Lienau et al., 2005; Seebeck et al., 2005). Because of the suspicion that bone quality may be a better predictor of hallux valgus correction success than patient age due to the importance of stable osteotomy site fixation, we designed the study described here to assess the influence of bone quality and donor age on Ludloff osteotomy sagittal plane stability and bending stiffness under controlled laboratory conditions. We hypothesized that bone mineral density would be a better predictor of bending stiffness and associated dorsal angulation in response to cyclic dorsiflexion bending moments than would donor age.

2. Methods

2.1. Specimen preparation

Thirty-one normal fresh-frozen cadaveric first metatarsals were used for this study, each from a different donor. Donor age ranged from 35 to 93 years; 17 donors were male and 14 female. After each metatarsal was dissected from the foot and stripped of soft tissue, its bone mineral density was quantified by dual X-ray absorptiometry (DEXA) scanning with a Lunar PIXImus small-animal densitometer (Lunar Corporation, Madison, Wisconsin, USA). Quality assurance testing was performed using a phantom with a known density. Each bone was then wrapped in saline-soaked gauze and refrozen at −20 °C until use.

2.2. Surgical procedure

The Ludloff osteotomy was created using an oscillating saw with a 0.4 mm-kerf blade, beginning dorsally at the level of the metatarsocuneiform joint and progressing distally, ending proximal to the level of the sesamoid apparatus. The osteotomy was stopped short of completion and the proximal fixation screw was inserted bicortically in a dorsal-to-plantar direction, perpendicular to the plane of the osteotomy. Fixation was achieved using DePuy Fusion and Reconstruction System (FRS) screws (DePuy, Inc., Warsaw, Indiana, USA). The FRS screws are cannulated and have cancellous leading threads with a diameter of 3 mm and cortical trailing threads with a smaller pitch and a diameter of 4 mm. The osteotomy was then completed, the distal fragment was rotated approximately 10° laterally about the proximal screw, and the distal screw was inserted bicortically from plantar to dorsal. The screws were tightened until the trailing threads were approximately flush with the cortex.

2.3. Mechanical testing

Between six and eight number 4 sheet metal screws were inserted into the base of each metatarsal, such that their shafts projected proximally, to ensure solid anchoring of the proximal fragment during embedding. The base of the bone was then rigidly embedded in a cylinder of polymethylmethacrylate dental cement (Fastray, H.J. Bosworth Co., Skokie, Illinois, USA) with the shaft of the bone angled 15° plantarward from the axis of the cylinder. A distally projecting rod fabricated from a modified 6.5 mm cancellous lag screw was then inserted tightly into the head and distal shaft, coaxial with the shaft of the metatarsal.

The embedded proximal end of the metatarsal was clamped to the table of a servohydraulic materials testing machine (Model 1321, Instron Corp., Norwood, Massachusetts, USA) such that the long axis of the bone was angled plantarward 15° from horizontal to approximate its position relative to the ground during the stance phase of gait. A linkage attached to the testing machine's actuator-mounted load cell, comprising a shaft with a spherical bearing at each end, was slipped over the distally projecting rod and fixed at a position 50 mm distal to the center of the head. An electronic clinometer (AccuStar, Lucas Control Systems, Hampton, Virginia, USA) was fixed to the end of the projecting rod to enable precise measurement of distal fragment angulation (Fig. 1).

Each metatarsal was subsequently cyclically loaded in cantilever fashion 1000 times, or until a predefined failure criterion was met, in a plantar-to-dorsal direction while continuously monitoring load and dorsal angulation. The effective peak load at the center of the metatarsal head during each load cycle was 31 N. This load magnitude is 1/3 of the mean Ludloff osteotomy fixation failure load determined by Trnka et al. (2000) in fresh-frozen cadaver first metatarsals and was selected to challenge the construct substantially 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, 100, 500, and 1000 were linear ramp loads applied at 7.75 N/sec, and all other load cycles were sinusoidal at 0.5 Hz. Failure was defined as interfragment angulation in excess of 10°, and cyclic loading was terminated in cases in which that degree of angulation occurred. The mode of failure was noted for each specimen that reached the failure criterion.

2.4. Data analysis

Angulation of the distal fragment at the 31 N peak applied load, presumed to indicate predominantly motion at the osteotomy site, was documented for each specimen on the 1st, 10th, 100th, 500th, and 1000th load cycles and the mean ($n = 31$) angulation calculated for each cyclic loading increment. For metatarsals that reached 10° of angulation prior to the 1000th load cycle, 10° was regarded as the angulation at the remaining cyclic loading increments for calculation purposes.

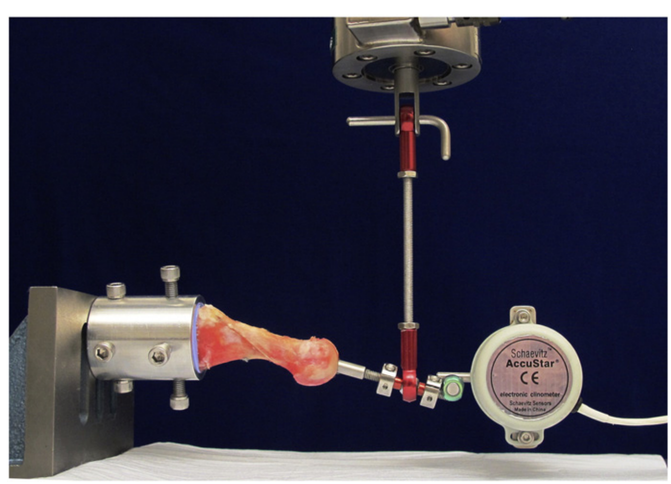

Fig. 1. Cyclic bending test setup. The metatarsal was angled 15° from horizontal, with its dorsal surface facing up and its base rigidly immobilized. Upward-directed force was applied to a distally-projecting rod at point 50 mm distal to the center of the metatarsal head. An electronic clinometer (right) continuously measured distal fragment angulation.