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Supplementary medial locking plate fixation of Ludloff osteotomy versus sole lag screw fixation: A biomechanical evaluation

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ABSTRACT

Background: The Ludloff oblique osteotomy is inherently unstable, which might lead to delayed union and loss of correction. Supplementary fixation to two lag screw fixation has been proposed. The hypothesis is that the osteotomy fixation constructs supplemented by a mini locking plate provide greater resistance to osteotomy gaping and loss of angular correction in response to cyclic loading.

Methods: Twenty fourth generation composite 1st metatarsals were used and underwent a Ludloff osteotomy. They were divided in two fixation groups: two lag screws (Group A), and with a supplementary mini locking plate (Group B). Specimens were subjected to either monotonic loading up to failure or to fatigue (cyclic) tests and tracked using an optical system for 3D Digital Image Correlation.

Findings: The osteotomy gap increased in size under maximum loading and was significantly greater in Group A throughout the test. This increase was observed very early in the loading process (within the first 1000 cycles). The most important finding though, was that with the specimens completely unloaded the residual gap increase was significantly greater in Group A after only 5000 cycles of loading up to the completion of the test. The lateral angle change under maximum loading was also significantly greater in Group A throughout the test, with that increase observed early in the loading process (5000 cycles). With the specimens completely unloaded the residual lateral angle change was also significantly greater in Group A at the completion of the test.

Interpretation: Supplementary fixation with a mini locking plate of the Ludloff osteotomy provided greater resistance to osteotomy gaping and loss of angular correction compared to sole lag screws, in response to cyclic loading.

1. Introduction

A number of proximal (Chow et al., 2008; Easley et al., 1996; Gallentine et al., 2007; Trnka et al., 1999) and diaphyseal (Chiodo et al., 2004; Robinson et al., 2009; Trnka et al., 2008) osteotomies have been utilized for the correction of moderate and severe hallux valgus deformities, but there are several issues regarding their mechanical instability, inadequate fixation and reduced healing potential which might lead to delayed union, dorsal malunion, or fixation failure with subsequent loss of correction (Chiang et al., 2012; Easley et al., 1996; Robinson et al., 2009; Trnka et al., 1999). The Ludloff diaphyseal oblique osteotomy (Chiodo et al., 2004; Robinson et al., 2009; Saxena and McCammon, 1997; Trnka et al., 2008) seems to be the most commonly used osteotomy (Pinney et al., 2006) (among foot and ankle surgeons in USA) for the correction of severe hallux valgus deformity. The procedure achieves deformity correction, pain reduction and functional improvement (Chiodo et al., 2004; Robinson et al., 2009; Saxena and McCammon, 1997; Trnka et al., 2008).

Several biomechanical studies have provided controversial data, with the Ludloff osteotomy fixed with two screws demonstrating superior (Lian et al., 1992; Hofstaetter et al., 2008; Scott et al., 2010; Trnka et al., 2000), equal (Acevedo et al., 2002), or even inferior (Trnka et al., 2000; Unal et al., 2010) biomechanics comparing to other commonly performed osteotomies. Like other proximal osteotomies, the Ludloff osteotomy is inherently unstable due to its geometry thus the entire load is transferred from the distal fragment to the proximal

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through the fixation device (Sammarco, 2008). This instability inevitably leads to irritation callus formation at the osteotomy site with a reported incidence of 16% to 26,7% (Chiang et al., 2012; Trnka et al., 2008). Delayed union is a well described complication with an incidence of 2%–6,7% (Chiang et al., 2012; Chiodo et al., 2004; Robinson et al., 2009; Trnka et al., 2008). Significant loss of correction of the intermetatarsal angle early in the postoperative period has been reported (Robinson et al., 2009), and it is interesting that in one study led to a recurrence in 26,7% of the patients (Chiang et al., 2012). Malunion requiring revision has also been observed with a reported incidence of 1.5% to 5%. (Chiodo et al., 2004; Trnka et al., 2008).

Our clinical observation in cases with inadequate fixation and mechanical instability of the Ludloff osteotomy, is that there is a tendency for the first metatarsal to rebound back in varus. The result is loss of the correction of the intermetatarsal angle (IMA). This observation along with the previously reported data have led us to modify the fixation of the Ludloff osteotomy by adding a small locking plate on the medial side of the metatarsal as a “medial buttress” (Stamatis et al., 2010). The theoretical advantages of such an application are: a. neutralization of the forces across the compressed osteotomy site with the lag screws thus improving the mechanical stability and b. “Buttressing” of the dorsal fragment preventing from rebounding in varus in the setting of lag screw loosening.

The purpose of this study was to quantify the mechanical stability of supplementary fixation of the Ludloff oblique diaphyseal osteotomy utilizing a mini locking plate paying attention to loading under fatigue conditions.

2. Methods

2.1. Surgical procedure

Twenty fourth generation synthetic 1st metatarsals (Sawbone, Pacific Research Laboratories, Vashon, WA) were used for the completion of the present experimental study. The synthetic metatarsals underwent Ludloff oblique osteotomy starting dorsally 2 mm distal to the level of the metatarsocuneiform joint, aiming distally at a 30° angle with respect to the axis of the metatarsal shaft. After completion of the dorsal two thirds of the osteotomy, a 2.7 mm titanium interfragmental screw (Synthes, Synthes GmbH, Switzerland) was inserted in a lag mode 6 mm distal to the dorsal osteotomy, but it was not fully tightened to allow the completion of the plantar one third of the osteotomy. After completion of the osteotomy, the distal (dorsal) fragment was rotated 5° laterally (lateral distal-fragment angle) around an axis formed by the 2.7 mm screw. Finally, a second stainless steel interfragmental compression screw (double threaded cannulated headless Barouk screw DePuy International, Leeds, UK), was inserted from plantar to dorsal, and the overhanging bone of the proximal (plantar) fragment was removed, leaving a flat medial surface on the metatarsal shaft. At this point the specimens were randomly divided into two groups with ten specimens each.

The specimens of Group A were tested as they were while the specimens of Group B underwent supplementary fixation with a 4-hole, 2.4 mm titanium mini locking plate (Synthes, Synthes GmbH, Switzerland) which was applied on the medial surface, with two screws (the most proximal and distal) inserted in the plantar and dorsal fragments, respectively (Fig. 1).

2.2. Mechanical testing

2.2.1. Monotonic loading up to failure tests

The mechanical tests were performed with the use of a servo-hydraulic load frame (Mini-Bionix 858, MTS Systems, Eden Prairie, MN) capable for applying quasi-static monotonic as well as cyclic (fatigue) loads. The applied load was measured with the use of a 500 N force transducer (MTS 661.11, Eden Prairie, MN). The specimens were fixed to the base of the load frame using a tilting vice to simulate the anatomical position of the 1st metatarsal during standing. Considering that the axis of loading corresponds to the direction of ground reaction forces and that a plane perpendicular to the axis of loading corresponds to the simulated ground, the samples were positioned in such way that their axis was forming a 15° angle with respect to a plane perpendicular to the loading axis (Acevedo et al., 2002). The load was applied at the distal-plantar side of the synthetic bones through a sphere (Fig. 2B).

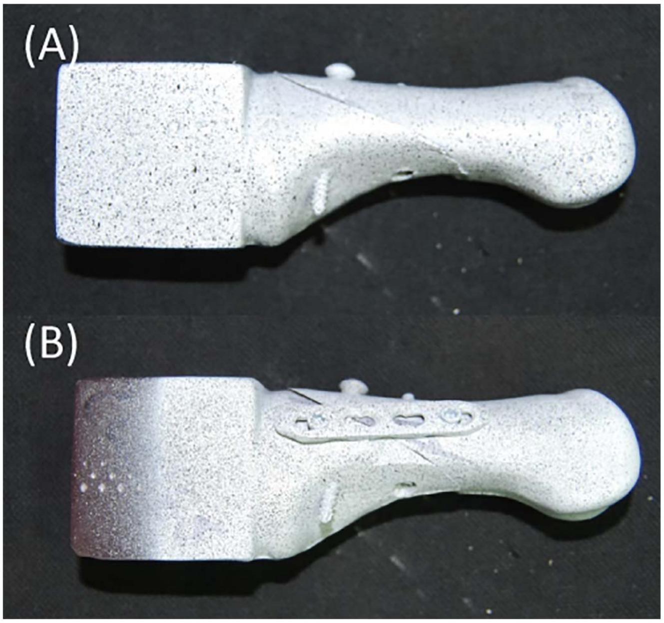

Fig. 1. Typical samples of Group A (top) and Group B (bottom). The specimens are painted with a stochastic/speckle pattern to enable the use of DIC.

The specimens' response to loading was studied with the use of an optical system (LIMESS Messtechnik und Software GmbH, Q-400-3D) for 3D Digital Image Correlation (DIC). 3D DIC is a contactless video-based technique for performing full field measurements of the displacements and strains developed during loading of a specimen. The specimen is covered with a stochastic/speckle pattern and viewed by two cameras that are positioned in a relative angle to one another ($\approx 40°$) (Fig. 2A, B). The 3D DIC system utilizes the stochastic/speckle pattern to define a set of “markers” on the surface of the specimen and map their 3D displacement field during testing. The measurement of out-of-plane displacements and strains is performed based on the principles of stereoscopic vision.

The loading conditions of the cyclic tests were defined with the help of a series of preliminary measurements. Three specimens of each group were tested until failure under monotonic quasi-static loading and their strength was assessed. The load-to-failure of the weakest construct was used as reference to define the maximum applied load during cyclic testing. More specifically the preliminary monotonic tests were performed under displacement control with a loading rate of 1 mm/min (Tsilikas et al., 2011). The displacement of the load frame piston, namely the grip-to-grip displacement and the resulted reaction force were recorded with a frequency of 1 Hz. At the same time the specimen was also photographed by the two cameras of the 3D-DIC system with the same frequency, (i.e. 1 Hz) (3A, 3B). The 3D DIC was used to calculate the opening of the osteotomy gap and the change of the lateral distal-fragment angle between the distal and the proximal part of the specimen. These calculations were performed based on measurements of the displacements (Ux, Uy, Uz) of four predefined points. All calculations were performed using specialised software Istra4D (LIMESS Messtechnik und Software GmbH). As it can be seen in Fig. 3C the osteotomy gap was calculated as a change in the distance between two points (a and b) at the plantar side of the specimen (one at each side of