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A biomechanical analysis of plate fixation using unicortical and bicortical screws in transverse metacarpal fracture models subjected to 4-point bending and dynamical bending test

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Abstract

In the published literature there are controversial data to the biomechanical stability of monocortical comparing to the bicortical fixation of metacarpal fractures. The aim of this study was to compare the biomechanical stability of monocortical and bicortical locking osteosynthesis in quasi-static and dynamic 4-point bending tests of composite third metacarpal bone (4th Gen third metacarpal, Sawbones, Malmö, Sweden) fixed with 7-hole locking plate (XXS System, Biotech-Ortho, Wright, Memphis, TN). The tests to determine quasi-static yield and bending strength as well as fatigue strength were conducted in 4 groups of 10 samples after creating standardized mid-shaft transverse osteotomies using a diamont belt grinder (0.3 mm saw blade). The force applied was the dorsal apex loading, similar to the forces applied to metacarpals during normal finger flexion and extension.

In the quasi-static testing, no plate breakage was observed in each group. All metacarpals broke at their thinnest part. The average bending strength of the bicortical samples (10.54 ± 0.998 Nm) was significantly higher comparing to the monocortical samples (8.57 ± 0.894 Nm) ($P < .001$).

In the dynamic loading test, all constructs (8 monocortical samples and 7 bicortical) that failed broke at the osteotomy site and the average fatigue strength did not differ in both groups.

Consequently, a unicortical plating method may provide adequate strength and stability to metacarpal fractures based on the results of the cyclical loading representative of in vivo loading.

Abbreviation: ASTM = American Society for Testing and Materials.

Keywords: bicortical locking osteosynthesis, biomechanical study, metacarpal fractures, monocortical locking osteosynthesis

1. Introduction

Despite the fact that metacarpal and phalangeal fractures are the most common fractures of the upper extremity,[1–3] there are very sparse published epidemiological studies on metacarpal fractures.[4] In the United States, 1.5% of all emergency department visits were hand fractures and 18% of these accounted for metacarpal fractures.[5] According to the retrospective study of de Jonge, the mean annual incidence rate of metacarpal fracture was 1.6% in the Netherlands.[6]

The 2 most common mechanisms of injury include accidental fall and direct blow.[4]

It is widely accepted that an adequate reduction of metacarpal fractures is needed to provide a good clinical outcome and to restore hand function. Undisplaced metacarpal fractures may be treated conservatively with cast immobilization in intrinsic plus position for 4 to 6 weeks but the nonstable, dislocated, or complex fractures require a surgical treatment.[2] We define as unstable the fractures that are prone to dislocation, for example, the spiral metacarpal fracture, dislocated the fractures that are displaced more that the half of the shaft width and complex the multifragment and intra-articular fractures.

Intramedullary k-wires, screws, or a dorsal plate osteosynthesis are the common options for stabilization of a metacarpal fracture.[7]

The purpose of the internal (plate) fixation of such a fracture is to restore length, alignment, and rotation and the dorsally applied plate provides the greatest rigidity in apex dorsal bending allowing early active motion.[8,9]

Beside anatomical considerations, the reason for applying the plate dorsally is the fact that the dominant force in hand movement occurs in digital flexion, so that the metacarpals of the hand are subjected to tension forces over the dorsal surface whereas the concave palmar surface experiences compressive forces.[2]

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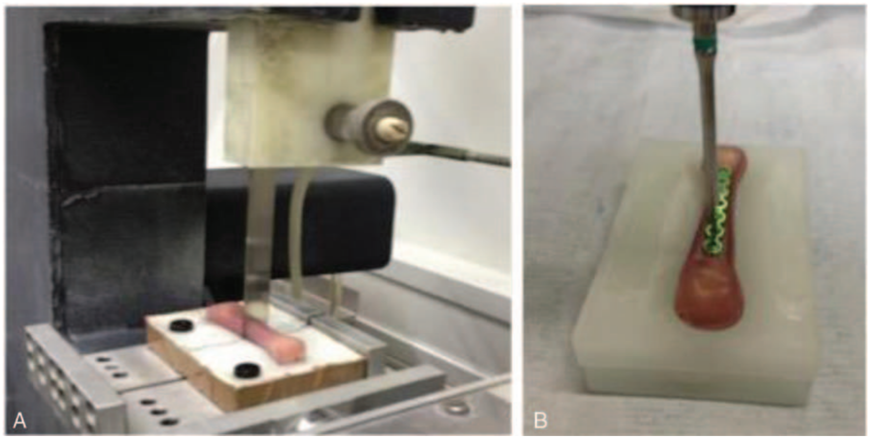

Figure 1. Midshaft transverse osteotomies were created using a diamont belt grinder (Exakt 310, Exakt, Norderstedt, Germany) with a 0.3-mm saw blade. The metacarpals were divided into 2 groups (group 1: bicortical fixation, group 2: unicortical fixation).

Management of these fractures focuses on restoring skeletal stability and hand function.[7] Therefore, it is important to offer a biomechanically stable osteosynthesis allowing bony union in good position, soft tissue healing, and early active hand rehabilitation in order to minimize the risk of internal scarring with joint stiffness and contracture.[10]

Locking plates in hand surgery are useful in some situations such as multifragment fractures or osteoporosis but it is still unclear if locking plates provide advantages in the treatment of common fracture patters in the young adult with healthy bone substance. And if using locking plates, the biomechanical superiority of bicortical (locking) fixation over unicortical (locking) fixation in transverse metacarpal fracture plating remains also a subject of debate.[2,10,11] Surgeons, who are not used to monocortical fixation get the feeling of "insufficient" stability, whereas bicortical fixation always include the risk of soft tissue affection on the palmar aspect due to the "rolling up" of nerves, vessels, or tendons with the drill.[10,12]

For that reason we carried out a biomechanical study with standardized midshaft transverse fracture in the composite third metacarpal bone (4th Gen third metacarpal, Sawbones, Malmö, Sweden).

The aim of this present study is to compare the biomechanical stability between monocortical and bicortical locking osteosynthesis of the midshaft transverse fracture by calculating yield strength and bend strength in the 4-point bending test and the fatigue strength in dynamical bending testing.

2. Methods

2.1. Specimen

Synthetic bones with comparable biomechanical properties were used in our study. The sawbones model (4th Gen Third Metacarpal #3416, Sawbones, Sweden) has elastic properties similar to real bone consisting of a mixture of glass fibers and epoxy resin and a standard cancellous material simulating natural cortical bone. Advantages are the avoidance of possible infections (hepatitis, human immunodeficiency virus) and frequent disinfection of the testing device associated with disconnection and resulting potential measuring errors as well as any measuring errors due to different bone structures, anatomy, or body weights. In that way, the bias of different size and consistence of the bone such as osteoporosis, which is evident in all above cited studies, are avoided. In addition, fixation in the same form is possible as the synthetic bones were identical. Because of the homogenous form, a significantly smaller standard deviation is achieved compared to human bones.[13]

A total of 40 samples were tested in our study. The 40 metacarpals were divided into 4 groups. The total number of 10 samples in each group was chosen based on the study of Afshar,[2] in which a statistical significance was proven using 10 samples in each group. An ethics committee was not necessary as we conducted a biomechanical study with composite third metacarpal bones.

2.2. Fracture generation and fracture fixation

Midshaft transverse osteotomies were created using a diamond belt grinder (Exakt 310, Exakt, Norderstedt, Germany) with a 0.3-mm saw blade to generate a standardized midshaft fracture (Fig. 1). In groups 1 and 2, metacarpals were plated bicortically using a 1.0-mm locking plate (XXS System, Biotech-Ortho, Wright, Memphis, TN) applied dorsally, shortened in a 7-hole plate and fixed with 3 screws (1.7 mm) proximal and distal to the fracture fragments. In groups 3 and 4, the plates are secured with unicortical screws. These screws were 6 mm long as the diameter of the narrowest part of the shaft is 7.8 mm. The embedding the samples in aluminum profiles and encapsulant (Technvi 4006, Heraeus Kulzer GmbH, Wehrheim, Germany) followed. The osteosynthesis was performed by the first and the fourth author (EL and BES).

2.3. Test setup

The samples of groups 1 and 3 were tested to failure using a quasi-static 4-point bending protocol. Four-point bending replicates better physiological loading and is selected in this study as a constant and pure bending moment is applied. In addition, the fracture site and the construct experience the same bending moment. On the other hand, 3-point bending places a peak compressive force and bending moment at the fracture site and the bending moment varies.[14] This testing was conducted with a universal testing machine (Zwick 1456, Zwick, Ulm, Germany) using a 4-point bending fixture (Fig. 2). The loading and support rollers were positioned with a center-span distance of 67 mm and a loading span of 30 mm on the aluminum profile, which was used for embedding the specimen (Fig. 3A and B).

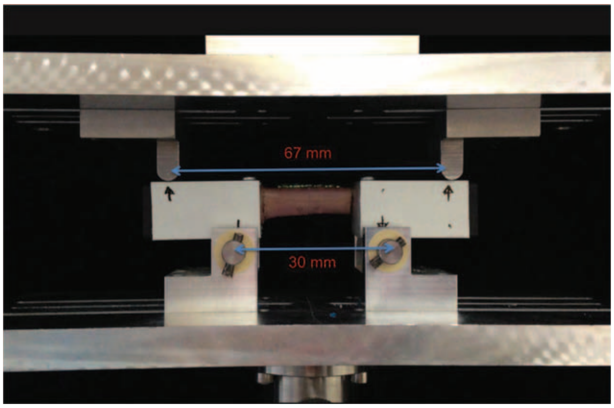

Figure 2. Apex dorsal 4-point bending tending to close the fracture gap is the clinically relevant loading mode.[14]

The samples were tested to failure with a constant displacement rate of 5 mm/min. Proof load and maximal load were determined from the load–displacement curve as described in the American Society for Testing and Materials (ASTM) Standard F382.[15] ASTM is an international standards organization that developing consensus technical standards for a wide range of materials. The set up of the quasi-static testing and cyclical loading is according to ASTM Standard F382 with the only difference that there were not only the plates tested but the whole construct (bone-plate-screw).

The samples of groups 2 and 4 underwent a dynamic bending protocol simulating the repetitive bending forces during early functional finger movements. The samples were loaded in flexion with a sinusoidal force according to ASTM 382 in the dynamic materials testing machine (DHM 100 824, Syscon easy Test software DHM, Clausthal-Zellerfeld, Germany) with a frequency of 2 Hz. Our test equipment was calibrated regularly.

The ratio of maximal loading to minimum loading was constantly 10:1. Failure was defined as a sudden loss of fixation, displacement of the fracture, or induction of a new fracture. The run-out limit was set to 10^6 cycles.

According to Little et al, 1 sample was used to find an estimate of the fatigue limit.[16] The initial load was set to 25% of the average bending strength (determined by the quasi-static 4-point bending test). If the specimen did not fail in 10^5 cycles (one-tenth of the run-out limit), the applied load was increased by 10% until this sample broke. The fatigue testing with the definite run-out limit of 10^6 cycles (using 8 samples) was started with the estimated load. After failure of a sample, the load for the next sample was reduced by 5% and if the sample did not break, it was increased by 5%.

The Wöhler curves (cyclic bending moment against the cycles to failure with logarithmic scale) for both groups were constructed according to ISO Standard 12107:2003 and the fatigue bending moment at 10^6 cycles was calculated.

Every step in our study was standardized, so that no variability in implementation exists.

2.4. Statistical analysis

SPSS version 21 (IBM, IL, Chicago) was used for the statistical analysis of the quasi-static test data. The results were checked for normal distribution by the Kolmogorow–Smirnow test. A t test was used to test for a statistically significant difference between the groups. The statistic evaluation of the results obtained from fatigue testing was done with the t test calculator (GraphPad Software, Inc, LA Jolla, CA). A P value <.05 was regarded as statistically significant.

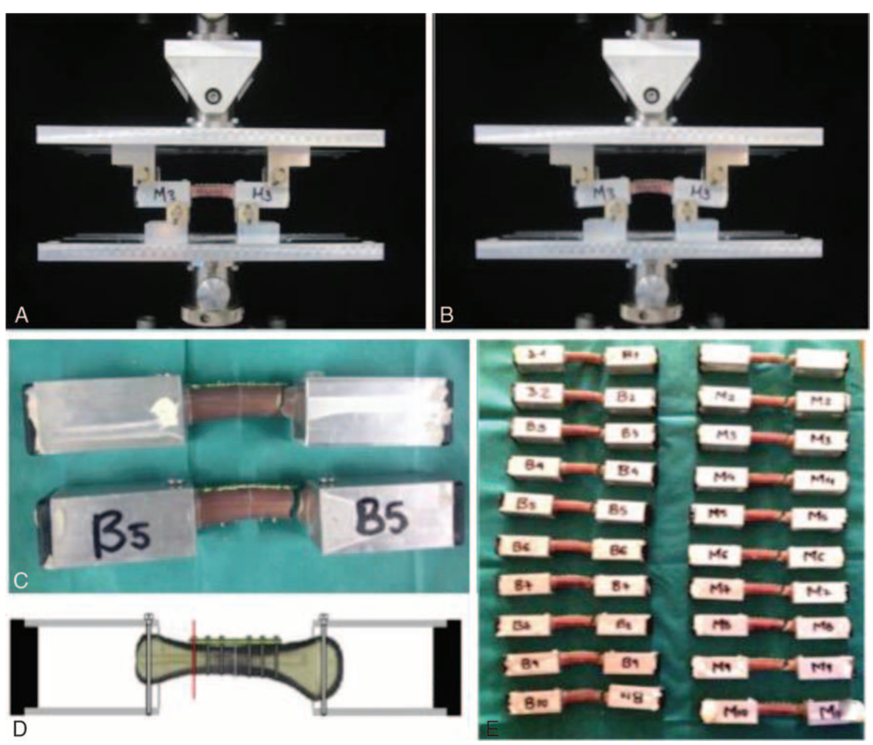

Figure 3. In the 4-point bending testing, the loading and support rollers were positioned according to the American Society for Testing and Materials F382 specifications. All these samples were tested to failure (A, B). No plate breakage was observed all metacarpals broke everytime at their thinnest part (C, D, E).

3. Results

3.1. Quasi-static testing

In the quasi-static testing, no plate breakage was observed. All metacarpals broke at their thinnest part (Fig. 3C–E).

The average yield strength (proof load) of the monocortical samples was 6.29±0.460 Nm and of the bicortical samples 7.00 ±0.700 Nm and differs significantly in both groups (P=.016, Fig. 4).

The average bending strength of the monocortical samples was 8.57±0.894 Nm and of the bicortical samples 10.54±0.998 Nm. The average bending strength of the bicortical samples was significantly higher comparing to the monocortical samples (P<.001, Fig. 3).

3.2. Cyclic loading

In the dynamic loading test, the average fatigue strength of the monortical samples was 1.645±0.1138 Nm (Fig. 5A) and of the bicortical samples 1.647±0.1765 Nm (P=.964, Fig. 5B). Two monocortical samples and 3 bicortical did not fail. All the constructs that failed broke at the osteotomy point (Fig. 6).

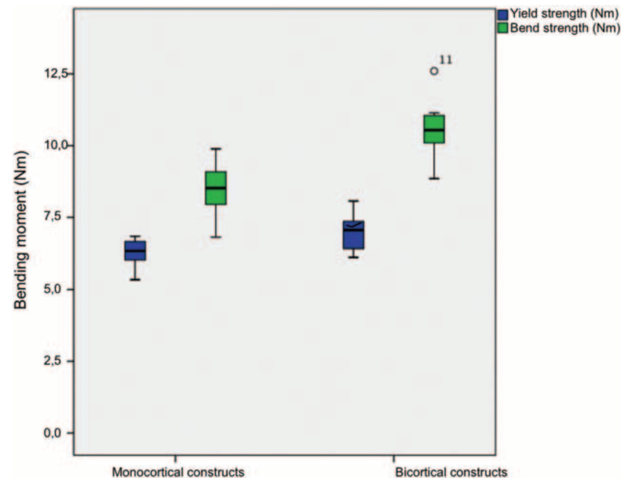

Figure 4. The average yield strength of the monocortical samples was 6.29±0.460 Nm and of the bicortical samples 7.00±0.700 Nm (P=.016). The average bend strength of the monocortical samples was 8.57±0.894 Nm and of the bicortical samples 10.54±0.998 Nm (P<.001).

4. Discussion

The aims of surgical treatment of metacarpal fractures should be the restoration of skeletal stability and biomechanically stable fixation allowing early hand functional treatment.[7]

The superiority of the biomechanical stability of bicortical osteosynthesis of metacarpal fractures over monocortical is still under debate.

In a study by Dona et al, midshaft transverse metacarpal fractures in 18 human cadaveric metacarpals were tested to failure with a 4-point bending protocol. In the 9 of these fractures, a unicortical plate screw osteosynthesis was applied and in the other 9 bicortical screws were applied. No statistically significant difference in the load to failure and stiffness was observed.[1]

In the study of Ochman, fresh second metacarpals from domestic pigs with locking monocortical and bicortical plates underwent a modified 3-point bending test. Also no significant difference for maximum load or stiffness was found.[10]

Testing with cyclic bending loads seems to be a closer representation of physiological loads during early functional movements.[2,11] For that reason, Afshar et al carried out a study, in which 20 cadaveric metacarpals underwent cycling loading. A biomechanical advantage was found when using bicortical nonlocking screws in metacarpal fracture plating compared with monocortical nonlocking.[2] In this study, the constructs were loaded with 100 N for 10 cycles and the load was raised for 100 N every 10 cycles. In a recent study, Doht et al used 40 fresh second metacarpals from domestic pigs in order to compare nonlocking and locking monocortical and bicortical plate screw osteosynthesis in a continuous cyclic loading for 1000 cycles. It was shown that the use of a locking plate with monocortical screw fixation could be an alternative to nonlocking plates with bicortical screws (load-to-failure after cyclic loading).[11]

To sum up, one study showed a biomechanical superiority of the bicortical nonlocking screws in metacarpal fracture plating comparing to monocortical nonlocking and the other showed a similar displacement of the mono- and bi-cortical screw fixation in locking and nonlocking plates.

Rotational stability is clinically relevant. On the other hand, in other published biomechanical studies of metacarpal fractures, the rotational stability was not proved, only the dorsal apex loading was studied.

For that reason, in our study, a quasi-static and a cyclic loading testings were included. Our results would suggest that a unicortical plating method may provide adequate strength and stability to metacarpal fractures based on the results of the cyclical loading representative of physiological loading. Adopting a unicortical plating method would simplify the operation, shorten the operation time (e.g., no need for correct determination of screw lengths), minimize the need for fluoroscopy, reduce

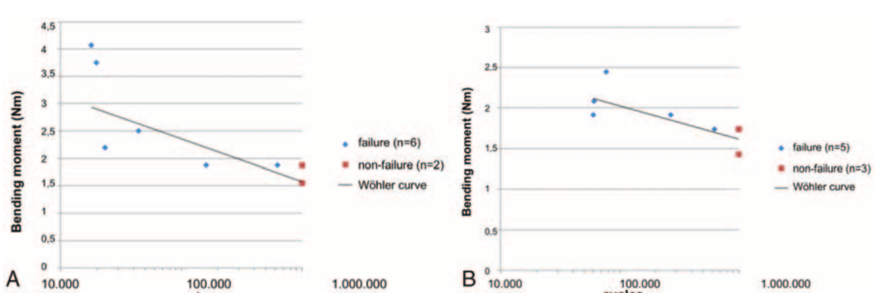

Figure 5. (A) The average fatigue strength of the monortical samples was 1.645±0.1138 Nm. Two monocortical samples did not fail. (B) The average fatigue strength of the bicortical samples 1.647±0.1765 Nm. Three bicortical samples did not fail.

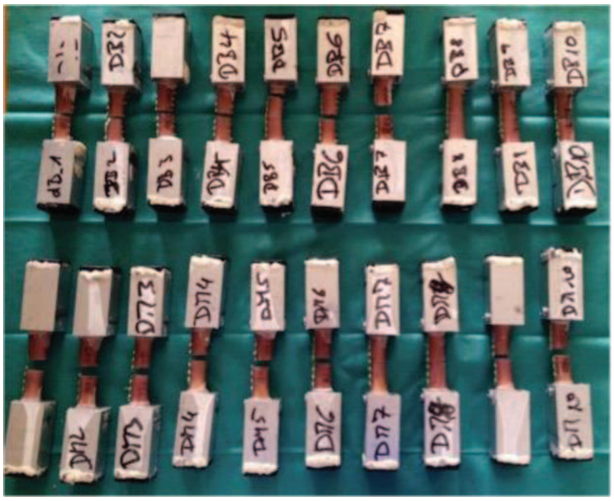

Figure 6. All the constructs that failed in the cycling loading test broke at the osteotomy point.

the costs, and avoid potential complications such as damaging anatomical structures (nerves, vessels, flexor digitorum profundus, and superficialis tendons) palmar to the metacarpals due to over drilling and oversized screws.[10,12]

A limitation of every in vitro biomechanical testing is the absence of soft tissue, ligament, and tendon interaction with the rigidity of the construct.[10] Another limitation in our study is the osteotomy used for producing a fracture and not following a fracture protocol. In addition, the synthetic bones did not conform to osteoporotic bones and therefore typical failure mechanisms such as screw break out/dislocation were not observed.[11] However, in practice, the main onset of metacarpal fractures is in the young adult without osteoporosis and osteoporotic fractures—if not suitable for conservative treatment—are mainly treated by minimal invasive methods with percutaneous k-wires or intramedullary nailing.

The low number of the constructs tested especially in the dynamic loading is no limitation in our study as the standard deviation is very low.

5. Conclusion

Our biomechanical study shows no difference in the biomechanical stability between mono- and bi-cortical locking fixation of metacarpal fractures in the cyclical loading regime. An advantage of our testing is the use of composite bones so that the only difference between the 2 tested groups was the different osteosynthesis.

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