Biomechanical evaluation of metacarpal fracture fixation: application of a 90° internal fixation model

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Abstract

Purpose Complications in metacarpal fracture treatment increase in proportion to the severity of the initial injury and the invasiveness of the surgical fixation technique. This manuscript evaluates the feasibility of minimizing internal fixation construct size and soft tissue dissection, while preserving the advantages of stable internal fixation in a biomechanical model. We hypothesized that comparable construct stability could be achieved with mini-plates in an orthogonal (90/90) configuration compared with a standard dorsal plating technique.

Methods This hypothesis was evaluated in a transverse metacarpal fracture model. Twelve metacarpals were subject to either placement of a 2.0-mm six-hole dorsal plate or two 1.5-mm four-hole mini-plates in a 90/90 configuration. These constructs were tested to failure in a three-point bending apparatus, attaining failure force, displacement, and stiffness. **Results** Mean failure force was 353.5 ± 121.1 N for the dorsal plating construct and 358.8 ± 77.1 N for the orthogonal construct. Mean failure displacement was 3.3 ± 1.2 mm for the dorsal plating construct and 4.1 ± 0.9 mm for the orthogonal construct. Mean stiffness was 161.3 ± 50.0 N/mm for the dorsal plating construct and 122.1 ± 46.6 N/mm for the orthogonal construct. Mean failure moment was 3.09 ± 1.06 Nm for the

dorsal plating construct and 3.14 ± 0.67 Nm for the orthogonal construct. The dorsal plating group failed via screw pullout, whereas the orthogonal failed either by screw pullout or breakage of the plate.

Conclusions When subject to apex dorsal bending, the orthogonal construct and the standard dorsal plate construct behaved comparably. These data suggest that despite its shorter length, lower profile, and less substantial screws, the orthogonal construct provides sufficient rigidity.

Clinical Relevance This study represents a “proof of concept” regarding the applicability of orthogonal plating in the metacarpal and provides the foundation for minimizing construct size and profile.

Keywords Metacarpal · Internal fixation · Orthogonal fixation · Biomechanics

Introduction

Metacarpal fractures are common, accounting for 18 % of all fractures of the hand and forearm [2]. Many of these fractures are amenable to non-operative treatment including closed reduction and immobilization. Acceptable radiographic and clinical parameters include angulation of less than 10°, less than 2 mm of axial shortening, bone apposition of 50 % or greater at the fracture site, and no malrotation [15]. Fractures that fail to meet these criteria following closed reduction may require operative treatment. Indications for operative treatment generally include irreducible or unstable fracture patterns, malrotation, multiple fractures, and isolated fractures in the setting of lower extremity trauma as these patients may benefit from early weight bearing and mobilization [14, 15].

Operative management aims to restore skeletal stability sufficient to achieve fracture union without loss of function. Such stability must be sufficient to allow for early

Therapeutic level: V

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mobilization and is typically attained with placement of a 2.0-mm, six-hole plate via a dorsal approach (Fig. 1) [10]. This configuration allows for purchase in six cortices proximal and six cortices distal to the fracture site. Despite relatively widespread acceptance of metacarpal internal fixation, clinical superiority in comparison to less-invasive methods including immobilization and percutaneous pinning has not been established [1, 6, 8, 11, 16, 19, 22, 24, 26]. Internal fixation is subject to a host of complications including hand stiffness, extensor lag, joint contracture, infection, and tendon irritation and rupture. These complications are related, primarily, to two factors: one, the severity of the initial soft tissue injury and two, the invasiveness of the fixation technique [18, 23].

The predominant force exerted on the metacarpal during motion protocols is one of apex dorsal bending during digital flexion with a distraction force across the dorsal metacarpal cortex and a compression force along the palmar metacarpal cortex [5]. Dorsal plating takes advantage of these forces, providing a tension band along the dorsal cortex that acts to resist the flexion force. This method of fixation, however, places a plate and associated screws directly underneath the extensor mechanism. This construct is often palpable and may result in extensor tendon irritation and, on occasion, tendon rupture [3, 4, 23]. Intramedullary techniques have been developed in an attempt to avoid these hardware-related complications; however, this technique is often difficult, is applicable to a limited subset of fractures, and has generally not attained widespread use among hand surgeons [9, 17, 21].

Orthogonal, 90/90, dual plate fixation has been utilized in the upper extremity for the treatment of distal humeral and distal radius fractures [12, 13, 20, 25, 27]. Placement of fixation at 90° provides for a significant rigidity and resistance to bending and torsional forces. Orthogonal construct design also offers the potential to decrease the size of the fixation, allowing for the use of lower-profile plates and shorter constructs. We hypothesized that comparable construct stability could be achieved with mini-plates in an orthogonal configuration compared with a standard dorsal plating technique.

This biomechanical study was designed to evaluate the feasibility of minimizing internal fixation construct size, while preserving the advantages of stable internal fixation. Conceptually, the experimental construct is designed to provide both a dorsal tension band and the additional strength of orthogonal fixation while reducing the overall length and profile of the construct through the use of mini-plates.

Materials and methods

Specimens

Six matched pairs of metacarpal bones were obtained from two fresh (unembalmed) human cadavers. Both cadavers were

Fig. 1 AO standard technique for fixation of a transverse metacarpal shaft fracture

female. The ages of the cadavers were 67 and 72, respectively. The index, long, and ring metacarpals were utilized. The thumb and small finger metacarpals were excluded due to significant anatomic variation. The metacarpals were exposed in situ with excision of the dorsal skin and extensor mechanism. Transverse osteotomies were created in the mid-shaft of each metacarpal using a saw, and fixation of each matched pair was performed in situ with either a Medartis® non-locking 2.0-mm six-hole plate (control, AO technique) or two Medartis® 1.5-mm non-locking four-hole mini-plates placed at 90° (dorsal and lateral); 2.0-mm screws were utilized in combination with the dorsal plate, and 1.5-mm screws were utilized in combination with the four-hole mini-plates. Plate characteristics are summarized in Table 1. All screws were placed in a bi-cortical fashion with the terminal dorsal screws divergent and the remainder of the screws perpendicular to the plate (Fig. 2). Plating was randomized for each matched pair. The metacarpals were then harvested and placed in saline prior to testing. Testing was performed on the same day as the fixation.

Test equipment

A three-point bending apparatus was used to load the samples in a Materials Testing System (MTS) servohydraulic test frame (Model 318.10S, MTS Corp., Eden Prairie, MN) (Fig. 1). The applied forces were measured with a uniaxial load cell (Sensotec Model 41/571-06, Columbus, OH), and the integral MRS linear variable differential transformer (LVDT Model 490.01, MTS Corp., Eden Prairie, MN) measured the actuator displacement.

Table 1 Plating construct characteristics

	Dorsal plate	90/90 mini-plate
Material	Titanium	Titanium
Thickness (mm)	1.0	0.6
Length (mm)	30	18
Dimension (mm)	2.0	1.5

Testing protocol

Each metacarpal was subjected to an apex dorsal, three-point bend-testing protocol. Each sample was mounted in the three-point bending fixture with the dorsal plate down and the transverse mid-shaft osteotomy centered under the loading pin (Fig. 3). The middle loading pin was then displaced downward via the MTS actuator at a rate of 10 mm/min until failure. Load and displacement were recorded at a sampling rate of 100 Hz. Failure was defined as any sudden change in the load-displacement curve.

Fig. 2 Plate placement: **a** dorsal plate, **b** 90° fixation **Fig. 3** Three-point bending apparatus: **a** schematic diagram, **b** testing setup

Data analysis

For each of the six pair-matched metacarpals, a load-displacement curve was generated. This curve was utilized to calculate the failure force (N), failure displacement (mm), stiffness (N/mm), and failure moment (Nm) for each construct. The peak failure force and displacement were the maximum measured force and the corresponding displacement (at the maximum force) during the test, and corresponds to an abrupt change in the load-displacement curve. The failure moment was computed, based on beam theory, as $M=FL/4$ where F is the failure force and L , the dorsal span (35 mm). Construct stiffness was determined as the slope of the linear region of the load-displacement curve before failure occurred.

Mode of failure was recorded for each specimen as screw pullout, plate failure (breakage), or metacarpal fracture.

Statistical analysis

Paired t tests were used to compare the biomechanical metrics (failure force, failure displacement, and stiffness) between the two plating construct groups. Significance for these comparisons was established on an alpha level of 0.05.

Results

Mean failure force was 353.5 ± 121.1 N for the 2.0-mm six-hole dorsal plating construct. Mean failure force was 358.8 ± 77.1 N for the 1.5-mm four-hole orthogonal construct. Failure

forces correspond with 36.1 and 36.7 kgf for the dorsal and orthogonal constructs, respectively. No statistical significance in mean failure force was determined with $p=0.909$ (Table 2).

Mean failure displacement was 3.3 ± 1.2 mm for the 2.0-mm six-hole dorsal plating construct. Mean failure displacement was 4.1 ± 0.9 mm for the 1.5-mm four-hole orthogonal construct. No statistically significant difference in mean failure displacement was determined with $p=0.213$.

Mean stiffness was 161.3 ± 50.0 N/mm for the 2.0-mm six-hole dorsal plating construct. Mean stiffness was 122.1 ± 46.6 N/mm for the 1.5-mm four-hole orthogonal construct. No statistically significant difference in mean stiffness was determined with $p=0.191$.

Mean failure moment was 3.09 ± 1.06 Nm for the 2.0-mm six-hole dorsal plating construct. Mean failure moment was 3.14 ± 0.67 Nm for the 1.5-mm four-hole orthogonal construct. No statistically significant difference in mean failure moment was determined with $p=0.909$.

In the 2.0-mm six-hole dorsal plating group, all six metacarpal constructs failed via screw pullout at the screw/bone interface. In the 1.5-mm four-hole orthogonal construct, three of six metacarpal constructs failed via screw pullout while three of six failed secondary to breakage of the plate. No constructs failed via fracture through the bone. Plate fracture consistently occurred at the screw hole corresponding with the narrowest portion of the plate (Fig. 4).

Discussion

Orthogonal fixation has been employed in the upper extremity, primarily in the treatment of distal humerus and radius fractures. Plates placed 90° to one another increase the cross-sectional surface area of the construct, adding significant rigidity. The stability afforded by an orthogonal configuration offers the potential to create smaller constructs while maintaining sufficient rigidity. This study applies the concept of orthogonal fixation to the metacarpal in an effort to reduce the length and profile of the fixation construct and compares this fixation to the AO standard technique of dorsal plating with fixation of six cortices proximal and distal to the fracture.

Prior metacarpal biomechanical studies have employed this three-point bending model [13] while others have examined four-point bending [5, 7] and cantilever bending [10, 22]. A three-point bending model was chosen for several reasons. First, the apex dorsal force replicates the primary displacement force placed on the metacarpal during active digital flexion. Second, three-point bending places maximal stress on the construct at the site of the osteotomy, specifically testing the strength of the construct at the osteotomy site. Third, the three-point fixture is simple and easily reproducible, and accommodates a variety of metacarpal morphologies. Four-point bending effectively disperses the force applied to the metacarpal and, therefore, does not maximally stress the construct at the site of osteotomy. A similar argument may be made against cantilever bending. While cantilever bending

Table 2 Three-point bending test results

Specimen	Failure force (N)	Failure disp (mm)	Stiffness (N/mm)	Failure moment (Nm)
Dorsal plate				
1-R2	313.9	2.691	237.3	2.75
1-L3	321.4	2.465	142.6	2.81
1-R4	213.9	1.966	103.1	1.87
2-L2	490.5	4.988	158.7	4.29
2-R3	512.6	3.153	201.7	4.49
2-L4	268.8	4.467	124.5	2.35
Mean	353.5	3.3	161.3	3.09
Std dev	121.1	1.2	50.0	1.06
90/90 plates				
1-L2	387.9	4.993	106.7	3.39
1-R3	405.4	2.644	183.3	3.55
1-L4	210.5	4.977	52.5	1.84
2-R2	422.8	4.683	165.3	3.70
2-L3	346	3.511	113.1	3.03
2-R4	379.9	4	111.9	3.32
Mean	358.8	4.1	122.1	3.14
Std dev	77.1	0.9	46.6	0.67
Paired <i>t</i> test	$p=0.909$	$p=0.213$	$p=0.191$	$p=0.909$

Fig. 4 Construct failure: note failure of the dorsal construct secondary to screw pullout in comparison to failure of the orthogonal construct secondary to fracture of the plate through the screw hole

may replicate the force applied to the metacarpal during active digital flexion, the necessity of mounting the metacarpal at its base places the location of maximal stress at the mount/bone interface rather than at the osteotomy site and, consequently, the metacarpal often fractures at the base prior to construct failure.

Failure force directly represents the applied force that is necessary to achieve loss of fixation and thereby loss of operative reduction. No significant difference was detected between failure force in the control dorsal plate construct in comparison with the orthogonal (90/90) construct. Failure displacement, the displacement of the metacarpal attained at the applied failure force, was comparable between the control and orthogonal constructs. A trend toward greater displacement was seen in the orthogonal group; however, this trend was not statistically significant, but may approach statistical significance if a larger number of specimens were tested.

Failure stiffness, the slope of the linear portion of the load-displacement curve, was also comparable between the control dorsal plate construct and the orthogonal construct. A trend toward greater stiffness was seen in the dorsal plating group; however, this trend was not statistically significant.

Failure moment is the most practical representation of the construct “strength.” Failure moment is derived from beam theory and represents the failure force displaced over a particular length (span). This measure quantifies the force at which applied stresses overwhelm the equilibrium of the system. In this model system, the failure moment measures the point at which the applied force exceeds the ability of the construct

(plate and bone) to resist failure. No difference was detected between the failure moment of the control construct and the orthogonal construct, implying that the two constructs resist failure equivalently.

This study has several limitations. The sample size is small with six metacarpals, limiting the power of the study. The lack of statistical significance does not markedly diminish the primary conclusion of this study: that an orthogonal mini-plate metacarpal construct can provide strength comparable to a standard dorsal plating metacarpal construct. The osteotomy was transverse and is not representative of significant comminution. The study also did not subject the metacarpals to cyclical loading, but rather examines stress to failure. This model is, therefore, more representative of catastrophic failure rather than failure from repetitive stress over time. In addition, quantification of soft tissue dissection was not performed, and therefore, no conclusion as to the degree of dissection necessary to place an orthogonal construct in comparison to a standard construct can be made.

The question of clinical applicability should be raised when considering any biomechanical model. In this instance, three pertinent clinical questions should be addressed. First, is there truly less periosteal dissection involved when placing two orthogonal plates in comparison with a single dorsal plate. Second, can orthogonal plates be effectively placed in situ. And third, does screw convergence between the dorsal and lateral plate interfere with plate placement. Periosteal dissection depends on the length of the construct and must be sufficient to allow for fracture reduction. Dorsal plating generally requires stripping of the dorsal periosteum as well as varying degrees of lateral periosteum. In some instances, the periosteum is dissected circumferentially to facilitate reduction. The mini-plate construct reduces the length of dissection necessary for plate placement, thereby reducing the length of scar immediately deep to the extensor mechanism, but may not truly decrease the overall extent of periosteal dissection. This construct can be placed with the metacarpal in situ, even on the non-border digits. All constructs in this study were placed with the metacarpal in situ. The radio-ulnar arch of the metacarpals allows for facile access to the lateral aspect of the long and ring metacarpals. In order to avoid screw convergence, the distal and proximal screws of the dorsal plate were placed in a divergent configuration. The remaining dorsal and lateral screws were placed perpendicular to the plane of the plate. No screw convergence was encountered in the dual plating technique.

This study is neither definitive nor infallible; rather, it represents a “proof of concept” that equivalent construct stability can be achieved with low-profile plates in an orthogonal configuration. In our opinion, these plates can be placed through shorter surgical incisions and with less periosteal dissection than is required for placement of a standard dorsal plate. Additionally, because of the thin dimension of the plates

and low-profile screw heads, the periosteum may be easily reapproximated over the construct decreasing palpability and to restoring of the gliding surface of the extensor mechanism.

Future research will focus on developing smaller constructs utilizing the relative strength of orthogonal fixation. Variations in plate placement or the addition of locking technology may play a significant role in maximizing stability. For example, placement of orthogonal plates at 45° off of the mid-axis may sub-serve both the tension band and orthogonal role, while avoiding plate placement directly beneath the extensor mechanism. Ultimately, employment of the orthogonal fixation offers the opportunity to customize fixation, reduce surgical dissection, and limit the soft tissue trauma associated with open fixation.

Conflict of Interest Andrew J. Watt, Randal P. Ching, and Jerry I. Huang have no personal relationship or financial interests to disclose.

Statement of Human and Animal Rights This study was conducted with approval from the Institutional Review Board. All tissues were treated and handled in accordance with Institutional Review Board recommendations for the handling of cadaveric subjects.

Statement of Informed Consent This study is a biomechanical, cadaveric study; therefore, no informed consent was obtained. All tissues were treated and handled in accordance with Institutional Review Board recommendations for the handling of cadaveric subjects.

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