RESEARCH ARTICLE

Comparative Bending Strength of Metacarpal Neck Fractures Fixed with Two Types of Intramedullary Screws

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Abstract

Objectives: Intramedullary (IM) screw fixation of metacarpal fractures is a technique, which has gained in popularity owing to its simplicity, speedy rehabilitation, and good functional outcomes. A new, larger diameter, non-compression screw designed specifically for IM metacarpal fixation was recently introduced which could provide better fracture stability and reduce the risk of hardware failure. Our goal was to evaluate the strength of this screw compared to a first-generation screw.

Methods: This mechanical study was designed to compare a 4.5 mm metacarpal headless screw (MCHS) to data from our prior research evaluating a 3.0 mm headless screw (HS). Accordingly, we used identical bone models, testing constructs, equipment, and protocols. A metacarpal neck osteotomy was created in 10 Sawbones models. A 4.5 mm x 50 mm MCHS was inserted retrograde to stabilize the fracture. Flexion bending strength was measured through a cable tension construct on a materials testing machine. Failure mechanism and strength was recorded and compared to data with a 3.0 mm screw construct.

Results: Eight models failed by bending of the intramedullary screw. Two models failed by rotation of the metacarpal head. Failure occurred at an average of 539 N (Range 315 – 735 N). The MCHS demonstrated a significantly greater load to failure compared to the previously studied 3.0 mm HS at 215 N ($P<0.05$).

Conclusion: A larger, 4.5 mm metacarpal-specific headless screw is more than twice as strong as a 3.0 mm diameter screw in a metacarpal neck fracture model.

Level of evidence: II

Keywords: Biomechanics, Hardware failure, Intramedullary screw, Metacarpal fracture, Metacarpal neck

Introduction

Intramedullary screw fixation of metacarpal fractures is a technique which has gained in popularity over the last decade owing to its simplicity, speedy rehabilitation, good functional outcomes, and low complication rate particularly compared to other commonly used techniques such as K-wire and plate/screw fixation.[1-12] The technique was first described in 2010 by Boulton and since then, both the technique and implants have evolved.[13] The initial headless screws (HS) used were borrowed from other applications, such as scaphoid fixation, and generally functioned well. Commonly used sizes were 2.4 and 3.0 mm diameter. Recently, a new metacarpal headless screw (MCHS) was introduced for metacarpal intramedullary fixation, with larger screw diameters and longer lengths designed specifically to the metacarpal anatomy. In addition, in contrast to other HS designs, this screw is not designed to compress the metacarpal fracture fragments, as compression is felt to be unnecessary and possibly detrimental causing loss of reduction in certain metacarpal

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fractures patterns.[6]

Our group previously investigated the strength of a 3.0 mm intramedullary HS in a metacarpal neck fracture model compared to two other common fixation techniques--plate/screw and K-wire fixation.[14] We found, like other studies, that the HS constructs were at least equivalent in strength to K-wire fixation, a well-established metacarpal neck fixation technique.[15,16] Clinical outcomes using HS for IM metacarpal fixation are generally excellent with a complication rate of 2.8%, consisting mostly of decreased range of motion and extensor lag.[17] Reported hardware failures include screw cutout, bent screw prior to healing, loss of fracture reduction, and abandoned IM screw use due to inadequate fixation stability.[1,7,8,12] Also, re-fracture of a previously healed metacarpal with a resultant bent or fractured screw has been reported in a recent systematic review at rate of 9 out of 603 patients, or 1.5%.[17] Given these hardware failures, our goal was to quantify the additional strength that a 4.5 mm diameter MCHS will provide compared to the smaller HS used in our previous study. A stronger construct would likely reduce hardware failure complications and allow a more aggressive rehabilitation.

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Materials and Methods

This mechanical study was designed to compare results from the current study, evaluating a 4.5 mm MCHS, to data from our prior research evaluating a 3.0 mm HS.[14] accordingly, we used identical bone models, testing constructs, equipment, and protocols. As the study progressed, we recognized that the MCHS construct was significantly stronger than the preceding HS construct and was failing at the bone/test fixture interface, not at the fracture site as planned. Consequently, we added an additional mid-metacarpal support, described below, which would not affect the measured failure strength of the fixation.

A metacarpal neck fracture was created in 10 fourth-generation composite Sawbones (Pacific Research Laboratories, Inc., Vashon, Washington) metacarpal models. To simulate a comminuted apex dorsal fracture, a standardized wedge of bone was excised at the meta-diaphyseal junction using a micro-sagittal saw and a 3-D printed custom cutting/fixation jig.[14] a small dorsal bone bridge was left intact to facilitate screw insertion. The fractures were stabilized with one 4.5 mm by 50 mm long MCHS (Exsomed, Aliso Viejo, CA) according to the manufacturer's recommended technique. A guidewire was inserted retrograde through the center, dorsal third location in the metacarpal head, a starting point shown to be collinear with the IM canal.[18] the wire was advanced through the IM canal and into the proximal metaphysis. We drilled over the guidewire with a 3.4 mm cannulated drill. A screw was inserted over the wire until it was countersunk in the head 2 mm. At this point, the small bridge of dorsal bone left in place to keep the metacarpal aligned during screw insertion, was cut with the oscillating saw. The proximal end of each bone model was secured to the base of a materials tensile testing machine (ESM 301 by Testing Machines Inc.) through specially designed grips.[14] A metal cable secured to the base of the machine was passed over the metacarpal head, then over a pulley, and secured to a wire grip on the actuator of the tensile testing machine. The metacarpal was aligned to ensure that when the slack from the cable was removed, the cable produced an angle of 85° as it passed over the metacarpal head. This arrangement was intended to simulate loading of the metacarpal bone by flexor and extensor tendon forces produced during grip.[14] During preliminary testing, we found the models were failing at the interface between the bone and the grips, so we added an additional metal bar support under the metacarpal midshaft to offload the grips and force failure to occur at the fracture [Figure 1]. This additional support changed the construct stiffness but did not affect failure strength of the screw fixation construct.

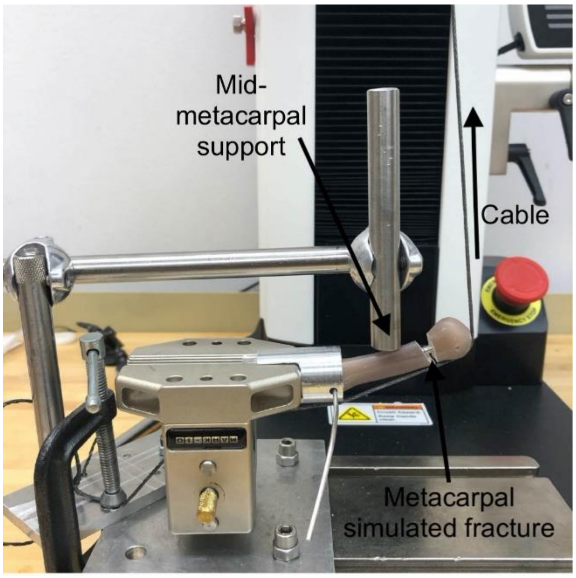

Figure 1. Testing construct -- Metacarpal base mounted in vice with midshaft support and cable running over metacarpal head

The force applied to the cable and cable displacement were measured via force and displacement sensors and digitally recorded. The models were loaded cyclically for 20 cycles at a rate of 0.5 mm per second with the force in the cable varying during each cycle from 0 to 40 N. This was done to simulate grip loading during immediate active motion exercises after fracture fixation.[19] following the cyclic loading phase, a progressive load was applied at a rate of 0.5 mm per second until failure. From the recorded cable force and displacement data, load to failure and displacement at failure were noted. Load to failure was defined as the maximum load on the metacarpal construct just prior to a precipitous drop in load value (construct failure). While we did calculate construct stiffness, we were not able to compare to our previous study data as the added support bar inherently altered the construct stiffness. However, comparison of failure loads at the fracture site are valid as this value is not affected by the added support. A Student t-test was used to compare load to failure of the MCHS and the previously studied 3.0 mm HS.

Results

The bone models demonstrated two different failure mechanisms. Eight models failed by bending of the intramedullary screw. Two models failed by rotation of the metacarpal head [Figure 2]. Failure occurred at an average of 539 N (Range 315 – 735 N). The stress /strain curves for the MCHS and previously studied 3mm HS are shown in [Figure 3]. Both constructs show similar characteristics with near linear stiffness (slope of the curve) up to the point of failure. However, the MCHS demonstrated a significantly greater load to failure of 539 N versus 215 N ($P<0.05$).

Figure 2. A) Metacarpal model, failure by screw bending. B) Metacarpal model, failure by head rotation

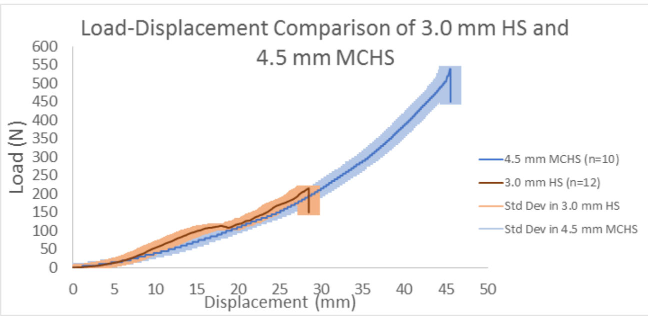

Figure 3. Strength comparison of 3.0 mm and 4.5 mm headless screw metacarpal construct

Discussion

When intramedullary screw fixation of metacarpal fractures was first described, the screws used were borrowed from other applications such as scaphoid fixation and small bone fusion. Accordingly, the screws were relatively small in size with 2.4 and 3.0 mm diameter screws most commonly used.[1,2,3-5,7-11,20] These screws functioned well but were not designed specifically for metacarpal IM fixation. Metacarpal hardware failures such as screw cutout, loss of fixation, and bent screws can be attributed to the screw design, poor surgeon technique, or overly aggressive rehabilitation. A recently introduced screw, designed specifically for metacarpal fixation, is the subject of this study. This screw comes in diameters (3.6 and 4.5 mm) and lengths (35 to 75 mm) appropriate for the IM canal of metacarpals and is designed, unlike other HS, to not compress. Compression is not required for IM metacarpal fixation and has the potential to be detrimental by shortening a comminuted fracture or displacing a well reduced oblique fracture. Initially HS were only designed in smaller diameters appropriate for small bone fixation, but now many manufacturers produce a variety of lengths and diameters appropriate for IM metacarpal fixation.

We found the average failure strength of the 4.5 mm MCHS construct (539N) is 2.5 times that of the 3.0 mm HS construct (215N). This is not an unexpected result as a basic engineering calculation of bending stress (stress is a function the moment multiplied by the distance to the neutral axis divided by the beam's moment of inertia—a function of the screw radius cubed) revealed an average strength of approximately three times greater. Other researchers evaluating HS of various sizes and different metacarpal fracture models and loading conditions showed a wide range of bending strength of 71 to 467 N, but generally of the same magnitude of the two screws we studied (215N to 539N) [14-16, 21-23] The average grip strength of a male age 20-29, the most frequent demographic to sustain a metacarpal fracture, is 451N force.[24] An individual metacarpal stabilized with a 4.5 mm MCHS can resist 539N per our results. Though the comparison of grip strength to individual metacarpal strength is complex, this result suggests that at time zero after fixation, the MCHS might potentially resist maximum grip.

Though first-generation metacarpal HS yielded good outcomes with a low complication rate averaging 2.8%, there are reports of hardware failure.[17] In their retrospective review, Warrender, *et al* reported hardware complications in 4 out of 160 patients (2.5%).[12] One patient had a presumed nickel allergy and screw removal. One patient healed asymptomatically with a malunion and bent screw. Two patients presented with a bent or fractured screw and new metacarpal fracture after repeat trauma requiring revision fixation. This scenario of re-fracture after successful healing occurred at a surprisingly high rate at 1.5% of 603 fractures according to a recent systematic review by Morway, *et al*.[17] These authors also reported that in 10 fractures where retrograde intramedullary screw fixation was attempted, the procedure was abandoned due to inadequate fixation or the intramedullary canal too narrow for the screw.[5,6,20] Though varied and inconsistently reported, most screws used in these clinical studies ranged in diameter from 2.4 to 3.0 mm. In our personal experience, in a practice of six hand surgeons who regularly use this technique, hardware failures also manifest as loss of reduction due to the screw not filling the canal, and cutout of the screw in the metacarpal head necessitating hardware removal.

A second-generation screw design meant specifically for metacarpal fixation could potentially address these shortcomings of first-generation metacarpal HS. Firstly, a larger diameter, canal filling screw that spans the length of the metacarpal would provide maximum stability and give the surgeon more confidence to start earlier rehab. Published therapy protocols after IM screw fixation of a metacarpal show no consensus, ranging from buddy taping and early motion to splinting and delayed therapy.[17] early motion protocols would accelerate return to sport for athletes and decrease the rate of complications associated with immobilization--joint contracture and extensor lag. Also, a larger diameter screw would provide more cutout resistance in the metacarpal head and reduce the rate of hardware failure (bending) causing malunion or re-fracture from new trauma. Unlike K-wires or an undersized HS, a screw sized appropriately to engage the inner cortex at the isthmus would provide resistance to shortening and rotation. It is yet to be seen clinically whether this or other larger headless screws reduce the complication rate. One potential downside to using larger screws for IM fixation is the creation of an overly stiff construct, limiting micromotion required for secondary fracture healing. Another consideration to using a larger diameter screw is creating a larger defect in the metacarpal head. A quantitative CT-based study showed that a 2.4 mm and 3.0 mm HS created a defect representing 8% and 12% of the total metacarpal head surface area, respectively.[25] Extrapolating this to a 4.5 mm screw yields a drill hole of at least 18% of the metacarpal head. However, the authors also indicate that the phalangeal base did not overlap the dorsally located countersunk entry site through most of the sagittal plane arc of motion, lessening the negative impact of the cartilage defect. For scaphoid fracture fixation, where a relatively large percentage of the proximal pole is drilled for headless screw fixation, HS have not led to arthrosis in long term follow up.[26] However, there are currently no long-term studies evaluating the outcome of IM metacarpal screw fixation with respect to joint arthrosis.

The strengths of this study include use a highly reproducible fracture model using Sawbones synthetic bones and a custom jig to create the fracture, as well as a proven loading construct.14 Potential concerns include the required modification of the testing construct. In theory, this addition should not affect the measured failure strength at the fracture site, though it is possible this modification could have altered the results in an unexpected way.

We investigated only a metacarpal neck fracture, so our conclusions do not necessarily apply to other metacarpal fracture types. In addition, we tested the models only in flexion loading, which is the most likely mode of failure. However, lateral bending and rotational loads could contribute to clinical displacement and failure.

Conclusion

As expected, we found the failure strength of the 4.5 mm MCHS (539N) is 2.5 times that of the 3.0 mm HS (215N). The significance of this finding is that the added construct strength might more confidently allow an early therapy motion and strengthening program, accelerating recovery and return to sports. The added strength of the 4.5 mm MCHS and metacarpal-specific design features would likely reduce fracture displacement complications. The potential drawback to use of a larger diameter screw is a bigger cartilage defect in the metacarpal head. Clinically, this has not shown to be a problem; however, there is no long term follow up on metacarpal IM screw fixation outcomes.

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Conflict of interest: None

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