A biomechanical study comparing plate fixation using unicortical and bicortical screws in transverse metacarpal fracture models subjected to cyclic loading

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Abstract
The use of bicortical screws to fix metacarpal fractures has been suggested to provide no added biomechanical advantage over unicortical screw fixation. However, this was only demonstrated in static loading regimes, which may not be representative of biological conditions. The present study was done to determine whether similar outcomes are obtained when cyclic loading is applied. Transverse midshaft osteotomies were created in 20 metacarpals harvested from three cadavers. Fractures were stabilised using 2.0 mm mini fragment plates fixed with either bicortical or unicortical screw fixation. These fixations were tested to failure with a three-point bending cyclic loading protocol using an electromechanical microtester and a 1 kN load cell. The mean load to failure was 370 N (SD 116) for unicortical fixation and 450 N (SD 135) for bicortical fixation. Significant differences between these two constructs were observed. A biomechanical advantage was found when using bicortical screws in metacarpal fracture plating.

Keywords
Metacarpal, unicortical screw, bicortical screw, cyclic loading, metacarpal plating

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Introduction
Metacarpal fractures are common injuries. Internal fixation by plating is an accepted method of treatment, especially in unstable fractures (Weinstein and Hanel, 2002). To withstand the high amounts of load produced in the hand during gripping, the implant must be able to withstand the forces which are transferred onto it. This is important to allow early active hand rehabilitation in order to minimise the risk of complications such as joint stiffness and contracture. As the dominant forces in hand movement occur in digital flexion, the metacarpals of the hand are subjected to tension forces over the dorsal surface whereas the concave palmar surface experiences compressive forces. Fixation of a metacarpal fracture using a dorsally applied plate provides the greatest rigidity in apex dorsal bending and has become the commonest method of internal fixation for unstable metacarpal fractures (Firoozbakhsh et al., 1993; Jones, 1987).

There have been previous studies using a single plate and double plates in combination with bicortical screw (BS) and unicortical screw (US) fixations (Fischer et al., 1999; Gajendran et al., 2009; Ochman et al., 2010; Prevel et al., 1995; Sohn et al., 2008). However, the biomechanical superiority of BS fixation over unicortical fixation in transverse metacarpal
fracture plating remains a subject of debate (Dona et al., 2004). Furthermore, the biomechanical properties of these fixations under cyclic loading have not been demonstrated. This is important, as cyclic loading is more representative of biological conditions than static loading. This study investigated the biomechanical strength of non-locking plates using unicortical and bicortical screw fixations subjected to cyclical loading in order to determine any superiority of one method over the other.

**Methods**

Ethical approval for the use of cadaveric metacarpals was obtained from the Cadaveric Research and Training Committee at the University Malaya Medical Centre (UMMC). Twenty human metacarpals from the index to little finger rays were harvested from three male cadavers of Indian race with a mean age of 63 years. The exclusion of the first metacarpal bone was an attempt to minimise inter-specimen variation in size. Any remaining tissue that was attached to the metacarpals was dissected. Before harvesting, the cadavers were kept in a refrigerator at −20°C. Immediately after harvesting the metacarpals were returned to −20°C for storage. The harvested metacarpals were then subjected to bone mineral density (BMD) scanning to ensure consistent bone density between the specimens.

**Fracture creation and plate screw fixation**

The metacarpals were randomly divided into two groups (Group 1 and Group 2) with equal pairs of metacarpals from each digit with similar lengths and diameters, which allowed matched comparison statistics to be applied (the corresponding metacarpal form the contralateral side was used as the counterpart, i.e. the right index metacarpal in Group 1 was matched with the left index metacarpal from the same cadaver in Group 2). Mid-shaft transverse osteotomies were then created using an oscillating saw with a 0.3 mm saw blade to create a transverse midshaft fracture model. In Group 1, metacarpals were plated using a Synthes 2.0 mm mini straight plate (Synthes, Solothurn, Switzerland) fixed with two screws proximal and distal to the fracture fragments. The bones were fixed such that the centre of the mini plate was overlying the osteotomy site. The screw holes were drilled using a standard 1.5 mm drill bit and tapped using a 2.0 mm cortical tap. All the plates in this group were secured with BS. In Group 2, metacarpals were fixed with similar plates using US (Figure 1).

**Cyclic three-point bending protocol**

All metacarpals were tested cyclically using a three-point bending protocol. The advantage of this set-up was that it concentrated the force directly onto the stabilised fracture. In addition, this force would seem to approximate the forces exerted at the fracture site in clinical conditions (Burstein and Frankel, 1971; Jones, 1987). The cyclic loading consisted of 100 N increments after every 10 cycles with 10 s of rest between each new load. The test was conducted at a rate of 1 Hz. A preload of 10 N was applied at the start of each cycle to ensure constructs remained in place throughout the experiments (Figure 2). Data acquisition was captured at 0.1 KHz and testing was performed until failure of fixation was achieved. Failure was defined using visual observation as well as noting the sudden drop in the resisted load (Calafi et al., 2010).

A load span of 26 mm was used as it was the longest span possible to support the shaft without interference from the polymethylmethacrylate (PMMA) cement blocks at the end of the construct. The transverse bending load was applied at the fracture site...
with the indenter approaching from the palmar aspect of the bone (Figure 3). The mechanism of fixation failure was based on the pattern of fracture. Modes of failure were characterised based on three main observations: screw cut-out from shaft and implant loosening (mode I); plate bending (mode II); and cortical fracture from the shaft (mode III). All loading was done using an electromechanical materials testing machine [Instron Microtester 5848 (Instron, Massachusetts, USA)] with a 1 kN load cell and a displacement resolution of 25 µm (0.0025 mm) over 10 mm travel. The measured value was rounded to the nearest 0.01 mm.

Results

Bone mineral density comparison

The mean and standard deviation for BMD was 0.24 (0.06) g/cm² in both the bicortical and unicortical groups, respectively, and was therefore not statistically significantly different using the two-tailed t-test.

Load to failure and plastic deformation

The highest load during cyclic loading that led to failure of fixation in the bicortical group was 700 N with a mean value of 450 N (SD 135). The highest load value in the unicortical group was 600 N with a mean of 370 N (SD 116). This was significantly different (p = 0.013). The evaluation of plastic deformation among the metacarpals was made at the second step when 200 N was applied (Table 1), as some metacarpal fixations failed at 200 N. The mean plastic deformation for the bicortical group was 1.52 mm (SD 1.01) and for the unicortical group it was 2.32 mm (SD 1.35). The difference between these two groups was statistically significant (p = 0.018 using paired t-test). Time versus displacement curves were plotted for each metacarpal and are summarised in Figure 4.

Modes of failure

The three modes of failure were identified in both the bicortical and unicortical groups (Table 2). In the unicortical group, most failures occurred due to screw cut-out (mode I), whereas the bicortical group failed mainly at the plate (mode II) and a smaller number failed by screw cut-out (mode I), resulting in implant loosening. The three failure modes are shown in Figure 5.

Discussion

Although non-operative management is acceptable for treating metacarpal fractures, it is not applicable in many cases, especially in the presence of fracture.

Table 1. Plastic deformation after cyclic loading with 200 N force

<table>
<thead>
<tr>
<th>Pair</th>
<th>Deformation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bicortical (n = 10)</td>
</tr>
<tr>
<td>1</td>
<td>1.16</td>
</tr>
<tr>
<td>2</td>
<td>1.03</td>
</tr>
<tr>
<td>3</td>
<td>0.93</td>
</tr>
<tr>
<td>4</td>
<td>0.77</td>
</tr>
<tr>
<td>5</td>
<td>2.38</td>
</tr>
<tr>
<td>6</td>
<td>0.93</td>
</tr>
<tr>
<td>7</td>
<td>1.55</td>
</tr>
<tr>
<td>8</td>
<td>4.05</td>
</tr>
<tr>
<td>9</td>
<td>1.52</td>
</tr>
<tr>
<td>10</td>
<td>0.92</td>
</tr>
<tr>
<td>Mean</td>
<td>1.52</td>
</tr>
<tr>
<td>SD</td>
<td>1.01</td>
</tr>
<tr>
<td>p-value</td>
<td>0.028</td>
</tr>
</tbody>
</table>

However, the use of metacarpal plating is not without its problems. Plate failure has been reported to be 8% (Fusetti et al., 2002) and other reported complications are tendon adhesion, tendon rupture, joint stiffness and non-union (Chinchalkar and Pipicelli, 2009; Page and Stern, 1998). Furthermore, overzealous drilling and use of improper screw length has been reported to cause flexor tendon rupture (Fambrough and Green, 1979). This has led some authors to explore the possibility of using unicortical plating. The reasoning behind this practice is that US fixation avoids damaging anatomical structures palmar to the metacarpal.

Figure 4. A sample time versus displacement curve for cyclical bending loading. Letters (i) and (r) represent irreversible (plastic) and reversible deformation, respectively.

Table 2. Mode of fixation failure

<table>
<thead>
<tr>
<th>Failure mode</th>
<th>Bicortical (n = 10)</th>
<th>Unicortical (n = 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screw cut-out from shaft with loosening (mode I)</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>Plate bending (mode II)</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Cortical fracture from shaft (mode III)</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

In addition to plating on the dorsal side, BS fixation has also been advocated (Firoozbakhsh et al., 1993; Prevel et al., 1995; Sennett, 1997). This is not unreasonable since BS fixation has been shown to provide superior pull-out strength in comparison with US fixation (Khalid et al., 2008). Since the palmar cortex is relatively thicker than the dorsal cortex (Lazenby, 2002), BS fixation strengthens the fixation by providing an increased area of screw contact, contributing to the superior pull-out strength observed.
Laboratory findings appear to support the use of this technique as it has been suggested that the mechanical strength of US fixation is no different to that of BS fixation (Dona et al., 2004). It can be argued, however, that these tests were based on a static loading regime, which is not a feature of physiological loading. In the present study cyclic loading was used, which demonstrated a significant advantage of BS fixation over US fixation. It is apparent that BS has an inherently higher pull-out strength as the result of the additional bone purchase on the palmar cortex of the metacarpals. It was also noted in this study that 90% of failures in the unicortical group underwent mode I failure (screw cut-out) as opposed to the bicortical group in which 70% failed via mode II (plate bending). These data suggest that the BS fixation provides a better hold in bone substance to a level such that failures are not the result of poor bone purchase, but rather as the result of forces exceeding the limits of the implant material.

To provide the advantage of both fixation methods, Ochman et al. (2010) showed in an animal bone model that unicortical locking screw plate systems offer comparable stiffness and load to failure to bicortical non-locking systems; however the cost of locking plate systems may preclude their use in some countries. Nevertheless locking plates should be considered the implant of choice for complex and comminuted fractures.

Despite the particular attention paid to the study design and details, there were several limitations observed in the present study that could not be avoided. Although oblique fractures are more common, a transverse fracture model was used in this study as it was easier to standardise. Dorsal US plating relies on the tension band effect of the plate, which will fail if there is palmar comminution of the fracture. Three-point bending was assumed to produce the physiological loading in this study.

Based on the work of An et al. (1985), it can be calculated that during grasp the bending moment at the mid-shaft of the index finger metacarpal ranges from about 5.6 to 20.9 Nm. That works out to about 174 to 652 N of force acting on the head end of the metacarpal from the midshaft. This is above the failure loads for the US plating group in this experiment. However to our knowledge no direct measurements of loads on metacarpals have been done.

Although BS was mechanically superior, the difference was only one-fifth greater than the US group. The loads acting on the metacarpal during rehabilitation may be lower than the reference value used, which was derived from grip strength testing. It is not possible to conclude from the available data whether US should be excluded from use, but data from this study could be used as baseline values for future studies on metacarpal fixation.

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**Conflict of interests**

None declared.

**References**


