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What is This?

Biomechanical comparison of three fixation techniques used for four-corner arthrodesis

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Abstract

Clinical results following four-corner arthrodesis vary and suggest that nonunion may be related to certain fixation techniques. The purpose of our study was to examine the displacement between the lunate and capitate following a simulated four-corner arthrodesis with the hypothesis that three types of fixation (Kirschner wires, dorsal circular plate, and a locked dorsal circular plate) would allow different amounts of displacement during simulated wrist flexion and extension. Cadaver wrists with simulated four-corner arthrodeses were loaded cyclically either to implant failure or until the lunocapitate displacement exceeded 1 mm. The locked dorsal circular plate group was significantly more stable than the dorsal circular plate and K-wire groups (p=0.018 and p=0.006). While these locked dorsal circular plates appear to be very stable our results are limited only to the biomechanical behavior of these fixation techniques within a cadaver model.

Keywords

Biomechanical, four-corner, fusion, wrist

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Introduction

Four-corner arthrodesis is a common salvage procedure for the arthritic wrist. The carpal bones included in the arthrodesis are the lunate, triquetrum, capitate, and hamate. Kirschner wires (K-wires), screws, compression staples or a dorsal circular plate (DCP) with screws may be used for bony fixation to provide stability at the arthrodesis site. The results in the literature vary depending in part upon the type of fixation used (Chung et al., 2006; Cohen and Kozin, 2001; Krakauer et al., 1994; Shindle et al., 2007; Vance et al., 2005; Watson and Ballet, 1984; Watson et al., 1999; Wyrick et al., 1995). Recent studies have suggested that higher rates of nonunion may occur with dorsal circular plate fixation (Chung et al., 2006; Kendall et al., 2005; Shindle et al., 2007; Vance et al., 2005) compared to more traditional techniques such as K-wires, staples or screws (Cohen and Kozin, 2001; Krakauer et al., 1994; Tomaino et al., 1994; Vance et al., 2005; Watson et al., 1999; Wyrick et al., 1995). While attention has been directed towards the biomechanical differences related to these implants, there has been no biomechanical comparison of these different methods of fixation.

Recently a radiolucent, nonmetallic (PEEK: polyether-ether-ketone, Trimed Inc., Valencia, CA, USA), locked dorsal circular plate (LDCP) has been introduced that uses locking screws and may improve the stability of the arthrodesis site over a non-locked circular plate.

While it would have been ideal to compare all possible different types of fixation, we chose to examine the characteristics of a traditional K-wire technique compared with a dorsal circular plate or a locked dorsal circular plate fixation.

Our hypothesis was that the three different types of fixation, used within a cadaveric four-corner arthrodesis model, would have significantly different amounts of displacement between the lunate and the capitate during simulated wrist flexion and extension.

Materials and methods

Cadaveric specimens

Nine paired fresh-frozen cadaveric wrists (four male, five female, mean age of 78.7 ± 11.3 years), were

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radiographically screened to exclude carpal malalignment or previous fracture. The specimens were then randomly allocated to three groups of fixation techniques used for four-corner arthrodesis: 1) four 0.045" (1.14 mm) K-wires; 2) DCP (Spider plate, Kinetikos Medical Incorporated, San Diego, CA, USA); and 3) LDCP (Xpode cup, Trimed Inc., Valencia, CA, USA). The characteristics of the cadavers and wrist specimen allocation are detailed in Table 1. This study was approved and monitored through our institutional review board. Specimens were examined fluoroscopically during fixation and before and after cyclical testing.

Surgical preparation

Each wrist was exposed through a dorsal longitudinal skin incision and ligament sparing capsulotomy. The scaphoid was excised and the lunate was aligned to the neutral position. The four carpal bones (lunate, triquetrum, capitate, and hamate) were then fixed together, without removing the cartilage (to maintain maximum joint congruence), with neutral lunocapitate alignment, using one of three fixation methods. In the K-wire group, four (0.045"; 1.14 mm) wires were used for fixation. In the plating groups the DCP and LDCP were applied and secured to the bones as described in the technique manuals for each device (Figure 1). For the LDCP, we used the largest diameter that could fit within the arthrodesis area without impinging against the radius. All DCPs and LDCPs had eight (2.4 mm) screws with two screws in each bone except for one LDCP where only seven screws could be used. The intra-articular space previously occupied by the scaphoid was used for positioning the sensor that monitored lunocapitate motion. A small magnetic rod was cemented (polymethylmethacrylate) into the radial aspect of the lunate and the transducer (HMC 1501; Honeywell, Solid State Electronics Center,

 Table 1. Cadaver wrist implant allocation

			Implant allocation		
Pair of cadaver	Age (year)	Gender	left	right	
1	98	М	K-wire	Spider	
2	64	F	Xpode	K-wire	
3	62	М	Spider	Xpode	
4	84	М	K-wire	Spider	
5	82	F	Xpode	K-wire	
6	80	М	Spider	Xpode	
7	85	F	K-wire	Spider	
8	68	F	Xpode	K-wire	
9	85	F	Spider	Xpode	

Plymouth, MN, USA) was secured within the radial aspect of the capitate. The capsule and skin were then closed with interrupted sutures.

Wrist simulator

The simulator was designed to apply cyclical wrist flexion and extension with torgue and displacement control, while static muscle loads were applied to the wrist flexor and extensor tendons. Labview software (National Instruments, Austin, TX, USA) was used to control and record the results. A stepper motor (open-loop) with timing belt pulleys was used for the mechanical drive-train, and a torgue cell attached to a small unconstrained X-Y table measured the torque at the wrist while allowing the flexion-extension motion to be unconstrained. The controller card for the stepper motor provided smooth acceleration of hand motion. This controller allowed the wrist to move through a slow arc of motion without abrupt changes in speed or direction. Angular motion was calculated by measuring the timing belt translation, which was then converted to an angle based upon the diameter of the timing pulley. The hand was attached to the torque cell by a vice-like clamping mechanism through the midmetacarpal region. A simulated mild compressive force was applied across the wrist using four pneumatic actuators (Airpel, Airpot Corp., Norwalk, CT, USA) sutured to the major wrist tendons which were assembled into four groups: 1) extensor carpi radialis longus (ECRL) and brevis (ECRB) sewn together; 2) extensor carpi ulnaris (ECU); 3) flexor carpi radialis (FCR); and 4) flexor carpi ulnaris (FCU).

Midcarpal motion monitoring

The hand was kept stationary and the forearm was allowed to move as it was easier to clamp the hand and move the forearm. We measured only flexion and extension. The carpal bones are very small, and when using the dorsal plates the plates cover most of the exposed dorsal surfaces. Therefore, we chose to place an electromagnetic transducer on the radial side of the lunocapitate joint, in the space left after excision of the scaphoid, to provide continuous monitoring of the motion (Figure 2). An electromagnetic transducer was used and provided continuous data output. The magnetic rod in the lunate and the transducer within the capitate were positioned to measure the lunocapitate motion. The output was quantified by correlating the output voltage to the orientation and relative motion of the magnet to the sensor orientation. Calibration curves were generated in a controlled lab-bench procedure to quantify the voltage



Figure 1. Fluoroscopic images of four-corner arthrodesis fixation: K-wires, DCP, and LDCP (radiolucent plate).



Figure 2. The electromagnetic transducer was secured into the radial side of the capitate. A magnetic rod was cemented into the radial side of the lunate.

to displacement using instrumented linear and rotatory precision slides.

Cyclical flexion-extension loading

The wrist extensors and flexor tendons were loaded with static tension using four pneumatic actuators to simulate a resting muscle tension across the wrist. A 15 N (total) load was applied throughout the test. This load was used to approximate the compressive force across the radiocarpal joint in normal wrist flexion and extension. We chose to apply loads that simulated a worst-case scenario type of loading: immediate motion with flexion and extension that could allow impingement and increased load across the arthrodesis construct. We applied 5000 cycles of wrist flexion-extension to approximate the number of cycles that might be applied to the wrist prior to union (Figure 3). This value was used as an estimate where the wrist is not immobilized and motion occurs 120 cycles a day, or 10 times per hour during 12 hours over 6 weeks. We also thought this might represent a reasonable number of cycles that might be applied to the wrist once a cast is removed and the arthrodesis is thought to be solid between 6 and 12 weeks after surgery.

The total arc of flexion-extension following fourcorner arthrodesis has been reported to have a range between 45% and 53% of the opposite side (Cohen and Kozin, 2001; Wyrick et al., 1995), or about 54° (Krakauer et al., 1994). With these values in mind, we decided to investigate a larger range of wrist flexion and extension (60° in each direction) to be certain to apply higher loads to the wrists. We felt that the increased flexion and extension would result in some impingement, either within the arthrodesis or where the dorsal carpal bones hit the dorsal radius, and cause increased torque or load and demonstrate fatigability of the fixation or implant. Consequently, the maximum end points of flexion-extension were each set to 60° , and the torque was limited to 100 N-cm. The torque limit was chosen based upon the weight of the hand (about 1 kg) and the center of gravity of the hand being about 5–10 cm from the radiocarpal joint. We estimated this torque, essentially equal to the hand dropping from extension to flexion under gravity. Each specimen was inspected visually and fluoroscopically at the completion of the cyclical loading which was defined as either completion of 5000 cycles, or by failure of the fixation with lunocapitate motion >1 mm or observation (visual or fluoroscopic) of hardware loosening or breakage.

Results

The age of cadavers in each group was comparable (*t*-test, p = 0.18 - 0.76).

Torque-rotation curve and fatigability

An example of the relationship between torque and rotation of the first 100 cycles from the DCP plate

experiment is shown in Figure 4. The endpoints of the first cycle were at 40° of flexion and 30° of extension, and then gradually there was an increase to 50° flexion and 40° extension at cycle 100 with relatively constant torque at 100 N-cm; this behavior demonstrates the fatigability of the simulated four-corner arthrodesis.

Lunocapitate motion

The lunocapitate motion at the end of the test is shown in Table 2 and Figure 5. When considering failure of the fixation as more than 1 mm, five wrists in the K-wire group and four wrists in the DCP group failed. No wrists in the LDCP group failed. The mean motion of the DCP plate group was less than in the K-wire group; however, this was not statistically significant (1.92 mm \pm 1.19 mm vs. $3.58 \text{ mm} \pm 2.15 \text{ mm}$; p=0.13). The LDCP group ($0.51 \text{ mm} \pm 0.22 \text{ mm}$) showed significantly less displacement when compared to the DCP and K-wire groups (p=0.018 and 0.006, respectively).



Figure 3. The specimen was mounted to the wrist simulator (A). The torque cell (arrow) was positioned under the center of wrist motion (B).

Mode of failure

We inspected each specimen at the completion of cyclical loading or at failure. Of the six specimens in the K-wire group, the pin which passed across the capitate and lunate was broken (three) or bent (one). The pin across the hamate-triquetrum was loose in three specimens. K-wire failures occurred early (<100 cycles) or late (>4000 cycles). The early failures were suspected to be due to early loosening of intact K-wires in bone and the later failures were associated with fatigue and breakage of the K-wires. Of the four specimens in the DCP group which failed, three had loose screws in the lunate, and one in the capitate (Figure 6). Two specimens in the DCP group and all of wrists within the LDCP group had no loose screws.

Characteristics of lunocapitate motion

In the K-wire group, the lunocapitate motion was similar to the wrist motion in flexion and extension



Figure 4. Torque-rotation curve of one specimen with a DCP demonstrates fatigability. The end points of flexion-extension gradually increase with relatively constant torque.

(Figure 7A). In contrast, the DCP specimens had almost no lunocapitate motion when the wrist was in the flexed position and an abrupt increase in volar gapping and displacement when more than 25° of extension occurred (Figure 7B). The LDCP specimens behaved similarly, but with less motion (less volar gap) in extension.

Discussion

There have been many reports in the last few years suggesting that inferior results may be related to the use of dorsal circular plate fixation for four-corner arthrodesis (Chung et al., 2006; Kendall et al., 2005; Shindle et al., 2007; Vance et al., 2005). For union to occur with a good clinical outcome, the surgeon must be certain to follow the basic principles of adequate preparation of the bone surfaces, reduction of the lunate, bone grafting and the proper insertion of the hardware (Merrell et al., 2008). With these thoughts in mind, this investigation was begun to simply provide biomechanical data to help understand the behavior of three types of implants that are used for four-corner arthrodesis.

Our results have shown that the LDCP was the most stable construct of the three tested and that there were no failures within the LDCP group. The wrists with the LDCP were significantly more stable in the lunocapitate region and had the least displacement measured between the lunate and the capitate compared to the DCP and to K-wire fixation. The predominant motion with plate fixation is volar gapping with wrist extension while volar and dorsal gapping is seen with both wrist flexion and extension with K-wire fixation.

The DCP group results included two of six specimens that completed 5000 cycles with similar final displacement to the LDCP group. These results are reflected by the clinical success which has been

Table 2. Lunocapitate motion (mm) either at the end of experiment (N=5000) or at the number of cycles at which the motion exceeded 1 mm

K-wire		Spider		Xpode	
final motion (mm)	failure at (cycles)	final motion (mm)	failure at (cycles)	final motion (mm)	failure at (cycles)
3.0	1	2.6	1201	0.5	Ν
6.0	6	0.5	Ν	0.2	Ν
6.0	1	3.0	406	0.9	Ν
3.8	5	2.5	2141	0.5	Ν
2.0	4001	0.3	Ν	0.4	Ν
0.7	5000	2.6	236	0.6	Ν
Mean = 3.58 mm \pm 2.51 mm		Mean = 1.92 mm \pm 1.19 mm		Mean = 0.51 mm \pm 0.23 mm	



Figure 5. Displacement (mm) between the lunate and capitate for the three fixation techniques.



Figure 6. (A) The K-wire between the lunate and capitate failed most frequently. (B) Loosening of the screws in the lunate was found in 75% of the failed DCP specimens.

observed (Merrell et al., 2008) in that the DCP can provide sufficient stability to achieve union. The remaining wrists with DCPs failed at a range of 236-1201 cycles due to screw loosening. Kirschner wires have been used for many decades and have provided good clinical results with a low rate of nonunion (Cohen and Kozin, 2001; Krakauer et al., 1994; Tomaino et al., 1994; Vance et al., 2005; Watson and Ballet, 1984; Wyrick et al., 1995). The displacement and failure of all but one specimen in this aggressive testing model does not negate the clinical success that has been associated with K-wire fixation, especially keeping in mind that patients with K-wire fixation (and all current methods of fixation) would be immobilized in a cast after surgery. The testing of the K-wire fixation was extreme and not expected

to produce similar stability to the plating techniques. The K-wire group was used mostly as a baseline reference.

Our results do not imply any higher rate of arthrodesis or lower complication rate with the LDCP. We have shown only that the LDCP is associated with less motion (more stability) in flexion and extension than four 1.14 mm K-wires or the DCP, and that no screws loosened or were broken in the LDCP plate as well.

Our study was limited in that we had a relatively small number of wrists and that we only measured displacement between two bones in flexion and extension. We also had relatively elderly cadavers with six of the nine in their eighth decade and the other three in their sixth decade. This suggests that



Figure 7. (A) Lunocapitate motion of one wrist with K-wire fixation (one cycle). (B) Lunocapitate motion of six specimens in the DCP group (during one cycle).

we may have had worse bone quality than the usual four-corner arthrodesis patient. We also applied loads to the wrists and implants that were probably higher than might be expected after surgery, especially as we routinely use postoperative casting following all methods of fixation. We feel the strengths of this study include a non-biased allocation of implants to cadaver wrists and that these relatively older cadavers represent perhaps a worst-case scenario regarding bone quality. While the cyclical loading was only in one plane, great effort was placed upon obtaining a non-constrained, torque limited arc of wrist flexion and extension. We did not specifically evaluate radiocarpal flexion-extension but rather the flexion-extension of the hand relative to the forearm. If there was a different proportion of radiocarpal motion between specimens this may have added more or less load to the midcarpal implant.

While the LDCP was the most stable of the three techniques tested, this does not predict clinical success. Surgeons must remain aware of the existing literature and principles governing four-corner arthrodesis operations.

The success of four-corner arthrodesis operations remains predicated upon careful preparation of the subchondral bone, correction of the wrist deformity and insertion of stable fixation. Locking screws do provide increased stability to the four-corner arthrodesis and this stability may ideally lead to improved union rates or decreased duration of immobilization. Perhaps most importantly though, the dorsal hardware must not be prominent or lead to impingement and requires careful inspection during insertion. We anticipate that our data and our model will be useful as we continue to investigate the outcome of surgical techniques for four-corner arthrodesis.

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Conflict of interests

None declared.

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