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Damage in a Distal Radius Fracture Model Treated with Locked Volar Plating after Simulated Postoperative Loading

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Abstract

Purpose—“Damage” is an engineering term defining a period between a state of material perfection and the onset of crack initiation. Clinically, it is a loss of fixation due to microstructural breakdown and can be indirectly measured as a reduction of stiffness of the bone-implant construct, normalized by the cross-sectional area and length of the bone. The purpose of this study was to characterize damage in a model of extra-articular distal radius fracture with dorsal comminution treated using two-column volar distal radius plates.

Methods—Ten matched distal radii were randomly divided into two groups: Group I specimens were treated with a Geminus® volar distal radius plate with an independent, two-tiered scaffold design; Group II specimens (contralateral limbs) were treated with an Acu-Loc2® volar plate with a single head design for enhanced ulnar buttressing. Specimens were cyclically loaded to simulate a 6-month post-operative load-bearing period. We report damage after a defined protocol of cyclical loading. Specimens were subsequently loaded to failure simulating a fall on an outstretched hand.

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Results—Group II specimens experienced significantly more damage or loss of fixation under cyclic loading conditions than Group I specimens. Group I specimens were significantly stiffer than Group II specimens under load-to-failure conditions. Ultimate force at failure in Group I and Group II specimens was not significantly different. Specimens failed by plate bending (Group I, n=6/10; Group II, n=2/10) and fracture of the lunate facet (Group I, n=4/10; Group II, n=8/10).

Conclusions—Group I specimens had less screw cutout at the lunate facet than Group II specimens under cyclic loading conditions as indicated by lower damage measures and fewer facet fractures during load-to-failure testing. Overall strength of construct is not affected by plate design.

Clinical Relevance—Microstructural damage or a loss of fixation due to an overly rigid volar plate design may cause mal-union or non-union of fracture fragments and lead to bone/implant instability.

Keywords

distal radius fracture; distal radius plating; volar locking plate; wrist biomechanics; wrist fracture

Introduction

Fractures of the distal radius are highly common in the United States with reports indicating that 1.5% of all emergency room visits were due to fractures of the hand and wrist, and 44% of those included the radius and ulna.^{1,2} Additionally, they account for up to 18% of fractures in the 65+ population and up to 25% of fractures in children.^{3–5} These fractures typically occur as a result of a fall on an outstretched hand (common in elderly population), sports related injury, and car accidents.^{6–8} While un-displaced or minimally-displaced fractures can be treated with a cast alone, displaced fractures, especially those with exposed bone or dorsal comminution, require surgical intervention.⁹

Volar locked plating, popularized by Orbay et al.^{10,11}, allows for positioning of the plate on the volar cortex of the radius while supporting the distal bone fragments containing the lunate and scaphoid facets. This technology has been evaluated biomechanically focusing on differences due to: dorsally placed plating systems^{12,13}, unlocked volar plate systems¹³, plate design^{14–17}, fracture type¹⁴, use of screws vs. pegs^{14, 15, 18}, and number of locked screws used for fixation^{19–21}. These studies independently found that the locked volar plating systems provide sufficient stiffness and strength for use in treatment of extra-articular and intra-articular distal radius fractures with and without dorsal comminution. To our knowledge, no studies have compared dual head to single head, two-column volar plate designs. Additionally, while many studies subject their specimens to cyclic testing prior to loading the constructs to failure, none have evaluated the effects that low load cyclic testing has on the overall stiffness and strength of the bone/implant constructs.

In the present study, we biomechanically evaluate two commonly used plating systems – the Geminus® standard, 4-hole volar distal radius plate (Skeletal Dynamics LLC, Miami, FL) and the Acu-Loc2® standard, 3-hole volar distal radius plate (Acumed LLC, Hillsboro, OR). The Geminus® plate uses a dual head design for independent two-tier scaffolding of the

lunate and scaphoid facets. The Acu-Loc2® uses a single head design for enhanced ulnar buttressing. Our evaluation includes quantifying the microstructural damage in each bone-implant construct under cyclic loading. “Damage” is an engineering term defining a period between a state of material perfection and the onset of crack initiation. Clinically, it is a loss of fixation due to microstructural breakdown and can be indirectly measured as a reduction of stiffness of the bone-implant construct, normalized by the cross-sectional area and length of the bone. We then examine how this damage affects construct stiffness and strength in subsequent ramped load-to-failure tests simulating a fall on an outstretched hand. Lastly, we examine patterns of failure in each bone-implant construct.

Materials and Methods

Specimen Preparation

Ten matched pairs (n=20) of fresh-frozen, cadaveric hands with forearms were used in this study. Specimens were thawed to room temperature and scanned using a Philips Brilliance 64-slice CT scanner (Cleveland, OH) for 3-D model development and morphometric measures. Each distal radius was segmented from reconstructed CT dicom data using the Materialise Interactive Medical Image Control System – MIMICS (Materialise, Plymouth, MI, USA). (Figure 1A) In the axial view, we scrolled proximally, 1.5cm from the distal articular surface of the segmented bone and used the MIMICS area measurement system to determine the cross-sectional area at the site of the simulated fracture for each radius. (Figure 1B) These values were used in subsequent damage calculations.

Distal radii were surgically removed from the forearm and sectioned 140mm proximal to the distal articular surface. An AO type 23-A3.2 extra-articular fracture was simulated by a 1cm dorsal wedge osteotomy created 1.5cm proximal to the distal articular surface.¹⁵ Specimens were randomized to two groups: Group I specimens were treated using a Geminus® volar distal radius plate (n=10); Group II specimens (contralateral limbs from specimens in Group I) were treated using an Acu-Loc2® volar distal radius plate (n=10). Three 3.5mm non-locking cortical screws secured the plates to the shaft through two holes (the two most distal shaft holes in Group I; both holes in Group II) and an oblong gliding hole. Seven 2.3mm threaded locking pegs were used to secure the plates to the distal fragment.

Mechanical Testing

Mechanical testing was performed under cyclic and ramped axial loading conditions using a servohydraulic test frame (MTS Systems, Model 858, Eden Prairie, MN) and 15kN load cell. The radial shaft was mounted in-line with the machine actuator. Load was applied through a custom fixture mounted to the load cell through an angle vise. The fixture ensured a load ratio of 60/40 through the scaphoid and lunate facets to replicate physiologic boundary conditions.^{22,23} The vise allowed for adjustment of the angle of the scaphoid/lunate contact points corresponding with geometrical differences in the radii. (Figure 2) Specimens were pre-loaded to 50N, held for 30 seconds and sinusoidally compressed with 50–250N, at a rate of 1Hz for 5,000 cycles to simulate a 6 month healing period. This load range was selected based on a studies suggesting that forces during light active motion of the wrist range from 100–250N.^{24,25} During cyclic testing the machine was halted every 500

cycles to obtain x-rays for post-hoc failure analysis (Hologic Fluoroscanner Premier Mini C-arm, Marlborough, MA). Bone/implant constructs not failed during cyclic loading were unloaded, held for 30 seconds, and subject to a ramped load-to-failure at 1mm/s simulating a fall on an outstretched hand. A Canon EOS Rebel T5i, set in continuous mode, was used for capturing the failure event during load-to-failure tests (Canon Inc., Tokyo, Japan).

Damage (D ; Eqn. 1) was calculated using the effective Modulus of Elasticity (E ; Eqn. 2) of the bone/implant constructs from hysteresis data at every 500th cycle.²⁶ The data was normalized by the effective modulus at cycle 5. This cycle was selected based on published data showing that settling of the bone and implant has occurred by the 3rd cycle.¹⁴

$$D = \left[\frac{E_{final}}{E_{initial}} \right] \quad (\text{Eqn. 1})$$

where E_{final} = Effective modulus at every 500th cycle

$E_{initial}$ = Effective modulus at cycle 5

$$E = \frac{PL}{A\Delta} \quad (\text{Eqn. 2})$$

where P = measured load, N

L = length of distal radius, 0.140 m

A = cross sectional area of distal radius at the location of fracture (measured using 3D modules from CT scans), m^2

Δ = displacement of bone as measured by actuator, m

Failure during cyclic loading was defined as catastrophic fracture of the bone or a decrease in the effective modulus (or stiffness) of greater than 90%. Stiffness and ultimate load data from ramped load-to-failure tests are reported. Experimental test data were analyzed with custom computer code to evaluate load-displacement hysteresis data and to calculate damage using Matlab® technical computing software (Mathworks, Natick, MA). A two-tailed, matched-paired t-test was used to determine statistical significance ($p=0.05$) between Groups I and II for stiffness and ultimate load data during ramped load-to-failure testing, respectively.

Results

Damage Analysis

Group II specimens experienced significantly greater damage (loss of fixation) under cyclic loading conditions than Group I specimens (0.78+/-0.11 and 0.66+/-0.10, respectively; $p=0.02$). Figure 3A shows a representative example of the force-displacement hysteresis curves for one specimen in each group with hysteresis data plotted at every 500th cycle. A reduction in stiffness due to microstructural damage is noted by an increase in displacement

under constant load. Figure 3B shows a representative example of the damage evolution for one specimen in each group, over the 5000 cycle test period. One specimen in Group II experienced volar lunate facet fracture during cyclic loading and was excluded from load to failure tests.

Load-to-Failure

Group I specimens were significantly stiffer than Group II specimens (481.47 ± 161.37 N/mm and 337.90 ± 112.04 N/mm, respectively; $p=0.04$). Ultimate force at failure in Group I and Group II specimens was not significantly different (1268.50 ± 307.69 N and 1025.63 ± 496.45 N, respectively; $p=0.11$).

Patterns of Failure

Specimens failed by distal fragment collapse leading to plate bending (Group I, $n=6/10$; Group II, $n=2/10$) and fracture of the lunate facet (Group I, $n=4/10$; Group II, $n=8/10$) (Figure 4).

Discussion

In the present study, we evaluated two-tiered (Group I) and buttress (Group II) type, two-column volar distal radius plates under cyclic and ramped load-to-failure conditions. We found that the two-tiered head design limited microstructural damage during low-load cyclic testing. Based on a pattern of failure analysis, it is likely that the damage induced during cyclic loading occurred at the lunate facet fragment in both groups, but was more prevalent in Group II. As described in the surgical technique guide for each implant, Group I plates have multiplanar screws that are distributed evenly to maximize subchondral bone support and Group II plates have parallel screws organized into a proximal and distal row with two diverging screws into the radial styloid to maximize screw number. We hypothesize that a mismatch between bone and plate/screw material properties coupled with a rigid buttress design in Group II plates may have induced damage to the lower strength bone in the lunate facet region. Slight flexion of the plates was observable in Group I specimens during cyclic loading. It is possible that the two-head design limited extreme plate/screw rigidity that can lead to high stress concentrations at the bone/screw interface. In order to more accurately determine the cause of the damage to Group I and Group II specimens, an advanced computational finite element analysis of the stress at the bone/screw interface is necessary. While damage was induced at a greater level in Group II specimens during cyclic loading, it is important to note that the damage did not affect overall construct strength as indicated by a non-significant difference in failure strength between both groups. Clinically, microstructural damage or a loss of fixation may cause malunion or non-union of the fracture fragments. Nevertheless, results of our simulated fall on an outstretched hand show that if a patient is subject to high impact loading of the distal radius during this period, both constructs would limit catastrophic failure to the same extent.

Our study has several strengths. First, this matched, paired study allowed us to compare the two implant designs on specimens from the same donor. This limited variability in tissue quality commonly associated with cadaver studies. Second, we simulated the lunate/

scaphoid load distribution based on proven physiologic measures. This allowed us to isolate failure patterns by facet region. Lastly, by normalizing the effective modulus by the cross-sectional area and standardizing the distal radius length, we better captured the level of damage experienced by each specimen.

Our study has a few limitations. We used cadaveric specimens for this study so we are unable to simulate healing. It is possible that the effects of healing may limit the damage induced in Group II specimens by offsetting the effects of the material property mismatch. Additionally, dorsal comminution with no bone graft/filler simulates the worst-case scenario. It is possible that performance may differ with interposed material.

Our study design was modeled after that of Dahl et al.¹⁵ who evaluated 8 traditional volar plate designs under cyclic loading followed by ramped load-to-failure using fourth-generation synthetic bone models. They found that bone/implant stiffnesses ranged from approximately 200 N/mm to 350 N/mm following 6000 cycles of loading in 2000 cycle increments of 100, 200, and 300 N. Our stiffness results compare favorably with this study. We found that bone/implant stiffnesses averaged 481 N/mm and 348 N/mm, respectively, after cyclic loading up to 250 N for 5000 cycles. Stiffness results of our testing also compare moderately with those of Wall et al.²⁷ who found that fixed-angle volar plates with bicortical screws had a stiffness of 230 N/mm following 1000 cycles of loading up to 250 N. The Wall et al. study used foam bone models of the distal radius meant to simulate osteoporotic bone and thus are slightly lower findings from ours.

It is important to note that, while the present study is validated by comparison of stiffness data with previous studies on a similar topic, this study is unique in that it quantifies the microstructural damage occurring in the bone during cyclic loading. This information may provide insight into the reasons for mal-union or non-union in some locked plate designs. Additionally, it may inform implant companies on designs of future volar locking distal radius plates such that the geometry can provide adequate stability without over-stiffening or significant rigidity that may lead to microstructural failure of the bone at the bone/screw interface.

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Figure 1.

A. Anteroposterior view of the hand and forearm showing the distal radius bone segmentation (purple) using the MIMICS software. **B.** Axial view of the wrist showing a 2D slice of the distal radius bone (purple) at the location of simulated fracture. MIMICS measurement tools were used to calculate the cross-sectional area of the bone at this location, for use in subsequent damage calculations.

Figure 2.

Experimental testing fixture showing radial shaft mounted to load frame actuator. The scaphoid/lunate load applicator is mounted to an angle vise to adjust contact angle to achieve 60/40 load distribution across the distal articular surface. A mini C-arm is positioned to obtain intra-cyclic x-ray images for failure analysis. A digital camera is positioned to capture failure during ramped loading.

Figure 3.

A: Representative force-displacement hysteresis curves of a single specimen from Group I and contralateral limb in Group II. A reduction in stiffness of each specimen is noted by the increase in displacement under constant loading. Note that the Group II specimen has a greater increase in displacement.

B: Representative damage plots of the same two specimens over the 5000 cycle test period. Much of the damage in each specimen accumulated within the first 1000 cycles with little damage progression after that period.

Figure 4. Representative images of the failed specimens showing **A.** distal fragment collapse leading to plate bending (Group I, n=6/10; Group II, n=2/9), and **B.** fracture of the lunate facet (Group I, n=4/10; Group II, n=8/9).