Effects of Distal Radius Malunion on Distal Radioulnar Joint Mechanics—An In Vivo Study

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ABSTRACT: Patients with a malunited distal radius often have painful and limited forearm rotation, and may progress to arthritis of the distal radioulnar joint (DRUJ). The purpose of this study was to determine if DRUJ congruency and mechanics were altered in patients with malunited distal radius fractures. In nine subjects with unilateral malunions, interbone distances and dorsal and palmar radioulnar ligament lengths were computed from tomographic images of both forearms in multiple forearm positions using markerless bone registration (MBR) techniques. The significance of the changes were assessed using a generalized linear model, which controlled for forearm rotation angle (-60° to 60°). In the malunited forearm, compared to the contralateral uninjured arm, we found that ulnar joint space area significantly decreased by approximately 25%, the centroid of this area moved an average of 1.3 mm proximally, and the dorsal radioulnar ligament elongated. Despite our previous findings of insignificant changes in the pattern of radioulnar kinematics in patients with malunited fractures, we found significant changes in DRUJ joint area and ligament lengthening. These findings suggest that alterations in joint mechanics and soft tissues may play an important role in the dysfunction associated with these injuries. © 2006 Orthopaedic Research Society. Published by Wiley Periodicals, Inc. J Orthop Res 24:1–9, 2007

Keywords: distal radioulnar joint; malunion; joint space; ligament; biomechanics

INTRODUCTION

Malunion of the distal radius is the most commonly reported complication of closed treatment for distal radius fractures.[1,2] Several studies have shown that clinical outcome is adversely affected by the severity of the malunion, most notably dorsal tilt and changes in radial length (shortening).[3–6] Malunion can lead to radiocarpal and radioulnar pain, as well as significant reductions in forearm supination and pronation.[7]

The kinematic changes in the distal radioulnar joint (DRUJ) caused by distal radius malunion have been examined in vitro in numerous laboratory studies, and include changes in the normal axis of rotation,[8] reduced joint congruity,[9] limited forearm rotation (prono-supination),[9,10] and altered strains in tissues of the triangular fibrocartilage complex (TFCC).[8,11] Increased dorsal tilt has been shown to lead to DRUJ incongruence, especially in cases where normal angulation changes 20° or exceeds 10° dorsal tilt.[9]

However, an in vivo analysis of radioulnar kinematics in patients with unilateral malunion of the distal radius and functionally limited pronosupination revealed no change in the location or orientation of the radius' rotation axis that was caused by the malunion.[12] Interestingly, no bony impingement at the sigmoid notch could be identified to explain the reduced range of motion (ROM). In both forearms of these patients, the rotation axis passed through the distal head of the ulna near its geometrical center. The fact that there was no appreciable change in the pattern of pronosupination kinematics, nor any evidence of bony

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impingement in this set of patients with clinically significant (>20°) distal radius malunion raises the following questions: What might be limiting forearm prono-supination? What might be the etiology for the patients' radio-ulnar pain?

We speculate that rather than alter the pattern of radioulnar kinematics, distal radius malunion changes the joint mechanics at the DRUJ. In particular, we suspect that after injury prono-supination may be constrained by changes in the soft tissues that stabilize the DRUJ, and that the pain may ultimately be due to alterations in joint loading and/or joint contact. Accordingly, the purpose of this study was to test the hypotheses that the interbone joint spacing is altered with malunion, and that malunion changes the computed dorsal and palmar radioulnar ligament path lengths.

MATERIALS AND METHODS

The outer cortical bones bone surface and 3D in vivo kinematic data from the nine patients in the previous study[12] were used to calculate the interbone joint space area, the location of the radius on the distal ulnar articular surface, and the path length and deflection of the dorsal and palmar radioulnar ligaments. These values were then compared between the malunited and uninjured forearm over the range of forearm rotation.

Patient Selection and CT Scanning

The inclusion criteria, patient data, and CT scanning procedures for the patients enrolled in this study are described in detail in a previous publication, as are the methods for markerless bone registration.[12] Briefly, after obtaining informed consent, subjects with unilateral distal radial malunions were recruited into the study. Clinical eligibility included a history of a unilateral distal radius fracture, without fracture of the sigmoid notch, treated by closed reduction and casting. Subjects were included if standard plane radiographs revealed a healed, malunited distal radius fracture with ≥15° dorsal angulation of the radiocarpal articular surface relative to the long axis of the radius, and radial shortening of more than 2.0 mm. Patients were specifically excluded if they had significant fractures of the ulnar head, neck, or shaft; however, ulnar styloid tip fractures were allowed. Patients with a history of injury to the contralateral wrist or distal forearm were also excluded. Goniometer measurements were made of wrist ROM (pronation-supination, radial and ulnar deviation, and flexion-extension).

Nine subjects (six women and three men) were included in the analysis (mean age 55.2 ± 15.4 years, range of 31 to 75). All were right handed, and the dominant hand was affected in 44% (4/9). Five of the nine had extra-articular fractures, while the remaining four fractures extended into the radiocarpal joint. Five had ulnar styloid fractures, limited to the tip of the styloid. The median time from injury to CT scanning was 10.0 months. Eight of the nine participants were scanned within 20.3 months of their wrist fracture; one was scanned after an interval of 11.4 years. Radiographically, there was an average of $21 \pm 6°$ (range 15–30°) of dorsal angulation, radial inclination averaged $17 \pm 5°$ (range 10–20°), and radial shortening averaged 5 ± 3 mm (range 2–8 mm). Forearm rotation was measured by sighting down the bi-styloid to bi-epicondylar axis, and comparing the two axes in supination and pronation. Clinically, the average range of motion of the injured wrist was $75 \pm 25°$ pronation and $73 \pm 23°$ supination, compared to full rotation (on average of approximately 90° for both pronation and supination) of the uninjured wrists. Five of the patients complained of functional limitations in their injured wrists. Three patients had marked decreases in grip strength (25–75% of contralateral).

CT scans of the distal radius and ulna of both wrists were obtained simultaneously. During scanning, the subject's forearms were supported on a custom designed wrist positioning jig, which included a pair of protractor-indexed handgrips to facilitate positioning in pronation and supination. Scans were performed with the forearm and wrist in the neutral position, as well as at targeted positions of 30, 60, and 90° in pronation and supination. In subjects with limitations in pronation or supination, scans were made at the 30° intervals, and then at the maximum rotation that could comfortably be achieved.

Kinematic Analysis

3D kinematics of the radius relative to the ulna, with respect to the neutral position, were determined at each static position of supination and pronation using well-accepted methods of markerless bone registration.[12–14] To simplify comparison of the malunited and uninjured wrists, the CT volume of the left wrist from each subject was mathematically transformed so that it looked like a right wrist.[12–14] In brief, the transformation involved multiplication of the X coordinate of the bone surface contours by -1 and reversing the direction of the contours in each CT image slice. This transformation made the bone shapes and motions of the left wrists directly comparable to the right wrists.

Joint Space Area and Centroid Location

Joint congruity was quantified using two measures of joint spacing: joint interbone spacing area and joint interbone spacing centroid location (Fig. 1). Joint interbone spacing area (JSA) was defined as the area on the surface of the ulna circumscribed by a distance contour reflecting 5 mm distance to the radius; interbone distances greater than 5 mm were not analyzed. The threshold distance of 5 mm was chosen because it was the smallest value at which the joint interbone spacing area for all patents and all wrist positions was nonzero. The location of the JSA was defined by the

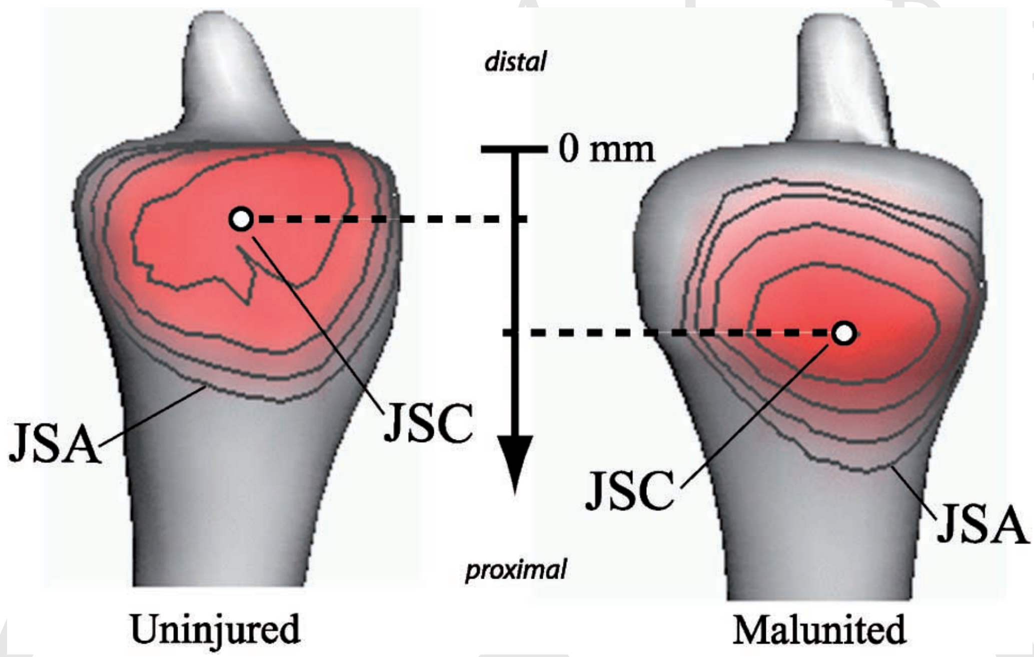

Figure 1. The articulation of the uninjured and malunited distal radial ulnar joint (DRUJ) was quantified using the area of joint's interbone spacing (JSA) and the location of the centroid of this area, which we defined as the joint space centroid (JSC). The JSA was defined as the area on the surface of the distal ulna enclosed by a 5-mm interbone distance contour. In both figures the largest contour is at 5 mm. Also visible are the 4-, 3-, and 2-mm contours. In the ulnae rendered here, the subject's smallest interbone distance was >1 mm, so a 1-mm contour does not exist. The location of the JSC was defined with respect to the ulnocarpal surface in a distal (negative) to proximal (positive) direction.

location of the JSA centroid, which we named the joint interbone spacing centroid (JSC).

The measures of joint congruity and spacing were determined from interbone distances using bone distance fields.[15] To determine this, each bone surface was first reconstructed by fitting a manifold surface to the 3D cloud of bone surface points segmented from the CT volume images. Once the manifold surfaces were created, the signed minimum distance from the radius surface was calculated for points within a box surrounding the radius. The manifold surfaces provided accurate and mathematically smooth interbone distance information but are computationally expensive. We combined the manifold representation with interpolated distance fields, which are slightly less accurate but more intuitive and faster. To increase the speed of lookup operations, the distance fields were sampled on a regular grid. The distance, which is positive outside the bone surface and negative inside, was calculated at each of $50 \times 50 \times 50$ points on a regular grid within the box. Spacing of these grid points was 0.4 to 0.9 mm, depending on the size of the bounded bone. This volume data set, whose components were the signed minimum distances to the manifold surface, is referred to as the bone distance field. Then, for each point on the ulna manifold, the smallest distance to the radius was calculated from the bone distance field using tricubic b-spline interpolation of the sampled distance values. Finally, this continuous map of minimum inter-bone distances was then reduced using topographical iso-contours for 1-mm increments of interbone distance from the ulna to the radius.

Computed Ligament Path Lengths and Ligament Deflection

Dorsal and palmar radioulnar ligament path lengths were computed as the lengths of the shortest possible paths between the radial and ulnar insertion sites. In cases where there was no intervening bone, the shortest path was a straight line. In cases where there was intervening bone tissue, our analysis algorithm required the ligament to avoid penetrating the bone by wrapping around the bone with the shortest possible path (Fig. 2).

Selection of the ligament insertion sites was based on anatomic texts and cadaver dissections. The base of the ulnar styloid was chosen as the ulnar insertion site for both ligaments, and the dorsal and palmar prominences of the sigmoid notch were selected for the dorsal and palmar radioulnar ligament, respectively. Before settling on the specific sites for analysis, a parametric study was performed to verify that the calculated ligament path length was not overly sensitive to insertion site location. To do so, the insertion sites were varied over a 4-mm diameter area and the radius was rotated through

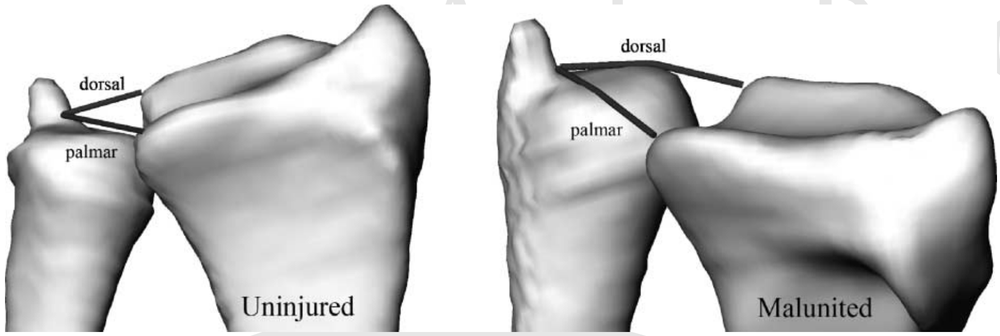

Figure 2. The computed path of the dorsal radioulnar ligament wraps over the head of the ulna in the malunited forearm of this typical subject. The ligament paths were calculated as the shortest path between the insertion sites that avoided penetrating the bone by wrapping over the intervening bone surfaces.

the full range of pronosupination. Although the absolute lengths of the modeled ligaments varied in this parametric study, the changes in length of the ligaments during forearm rotation sites were consistent over supination-pronation. This allowed us to reduce our analysis to a single ligament fiber and single set of insertion sites for each wrist.

The shortest ligament path lengths, were computed via an optimization approach that exploits the bone distance-field representation.[15] To do so, a local 3D coordinate system was constructed with its origin at one of the insertion points. In this coordinate system the x_l-axis was defined by the straight-line vector between the two insertion points, the y-axis was any vector perpendicular to the x_l-axis, and the z_l-axis was the crossproduct of x_l and y_l. The ligament path was first constructed as N equally spaced discrete points along the x_l-axis. Then, an optimization routine was run over the y_l and z_l coordinates of the 40 points to minimize the Euclidean length of the path. However, this optimization was such that the location of each point on the ligament was forced lie outside of the bone surface. Ligament deflection induced by the constraint to prohibit bone penetration, was calculated as a measure of the amount of "wrapping" around the bone surface. Ligament deflection was quantified as the maximum normal distance between the computed ligament path to the x_l-axis.

Data Analysis

Positioning the wrist and the forearm for CT scanning using the jig-mounted protractor introduces variability in positioning on the order of $\pm 10^\circ$ in our previous studies.[12] Therefore, for analytical purposes the value of the independent variable of forearm position (supination-pronation with respect to neutral) was determined from the 3D kinematic analysis of the CT volume images and not from the protractor reading. Because forearm prono-supination at each preselected position was not consistent within or between subjects, we linearly interpolated the values of the four dependent variables (ulnar JSA, ulnar JSC, and radioulnar ligament lengths) for each 15° increment of prono-supination, from -90 to 90° of forearm rotation. Few patients were able to reach these extremes of motion with their injured forearm, so the analysis for both forearms was limited to a range of -60 to 60° of forearm rotation. Accordingly, the number of subjects varied at these 15° increments (-60°: uninjured = 6 and injured = 1; -45°: 9 and 5; -30°: 9 and 8; -15°: 9 and 8; 0°: 9 and 9; 15°: 8 and 8; 30°: 8 and 8; 45°: 7 and 8; 60°: 4 and 6). Our statistical analysis accounted for these missing values.

Statistical Analysis

Generalized estimating equations (GEE)[16] were used to compare JSA, JSC, and ligament path lengths in the uninjured and malunited forearms. GEE accounts for the correlations between repeated measures on each individual, as well as missing values, producing appropriate standard errors. An autoregressive correlation structure was used, because measures were taken at sequential forearm rotations, from the 60° of supination to 60° of pronation. All p-value $= 0.05$ were considered to be statistically significant.

RESULTS

In both the injured and uninjured wrists, the size of the ulnar joint interbone spacing area (JSA) did not change appreciably as the forearm was pronated and supinated. However, the size of the ulnar JSA in the malunited forearms was significantly smaller ($p < 0.01$) than that of the uninjured forearms at all positions of forearm rotation (Fig. 3). On average, the JSA on the ulna was approximately 25%, or 56 mm^2 [standard error (SE) 4.0 mm^2], smaller in the malunited forearms than in the contralateral uninjured forearms. The average ulnar JSA across all

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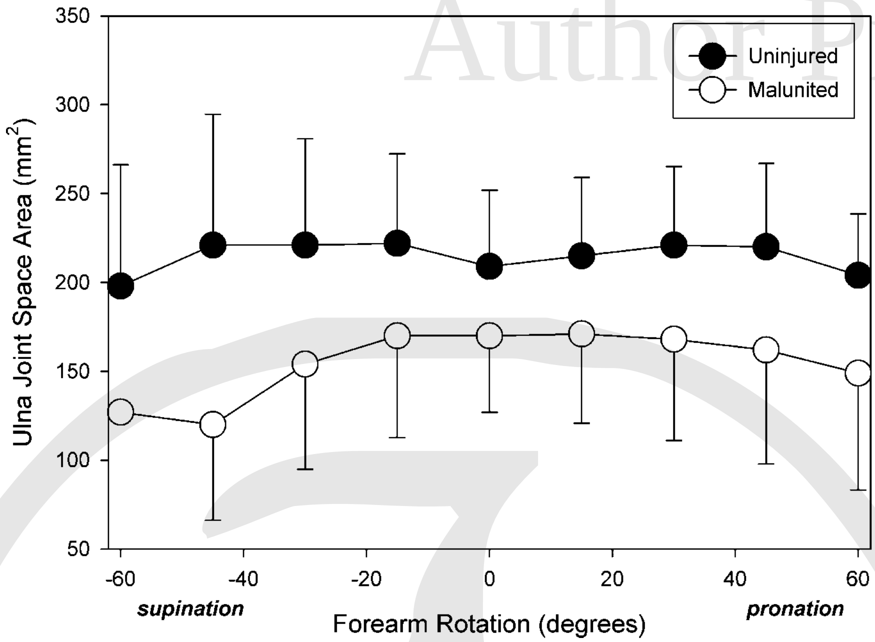

Figure 3. The distal radioulnar joint interbone distance area on the ulna (JSA) significantly decreased ($p < 0.01$) at all forearm positions with malunited distal radial fractures when compared to the uninjured contralateral side. The JSA did not significantly vary with forearm supination-pronation motion.

forearm positions in the malunited and uninjured forearms was 155 mm^2 and 215 mm^2, respectively.

The ulnar joint interbone spacing centroid (JSC) was located significantly more proximally in the malunited forearms than it was in the uninjured forearms at all positions of forearm rotation ($p < 0.01$) (Fig. 4). As with the size of the JSA, the JSC location did not move proximally or distally with forearm rotation in either group. The average JSC location in the injured forearms was 1.3 mm (SE 0.1 mm) more proximal than it was in the uninjured forearm. On average, the location of the JSC was 5.3 mm and 3.9 mm proximal to the ulnocarpal surface for the malunited and uninjured forearms, respectively. The palmar-dorsal location of the JSC was not significantly affected by injury, although for both the uninjured and injured wrists it did shift with prono-supination. At a forearm position of 60° of pronation the location of JSC had moved through a palmar angle of approximately 40° from its neutral position, and similarly at 60° of supination the location JSC had also moved dorsally approximately 40° from its neutral position (average values for all subjects). This suggests the location of the JSC (as described by a prono-supination angle) lagged behind the rotation of the forearm in both supination and pronation.

The computed radioulnar ligament path lengths varied as a function of ligament, injury, and forearm rotation. Most notably, the computed path length of the dorsal radioulnar ligament was an average of 3.9 mm (SE 0.3 mm) longer in the malunited forearms than in the uninjured forearms (Fig. 5A; $p < 0.01$). However, the computed path length of the dorsal radioulnar ligament increased similarly in both the malunited and uninjured wrists, by approximately 3 mm over 120° of forearm rotation from 60° supination to 60° pronation (Fig. 5A; $p < 0.01$).). We did find that the dorsal radioulnar ligament "wrapped" around the head of the ulna in all nine malunited fractures (with an average deflection of 0.5 mm (SE 0.5 mm), but in only two of the uninjured wrists (Fig. 2). In contrast to the dorsal radioulnar ligament, the computed path lengths for the palmar radioulnar ligament in the malunited and uninjured wrists were essentially the same, and they tended to be longest when the wrist was in neutral (Fig. 5B).

DISCUSSION

Clinical studies have shown that poor clinical outcomes, such as limited or painful forearm rotation and osteoarthritis of the distal radioulnar joint (DRUJ), are associated with malunited distal radius fractures that heal with >20° of dorsal tilt, 5 mm of ulnar variance, or loss of more than 10° of radial inclination,[3–6,17] especially in young,

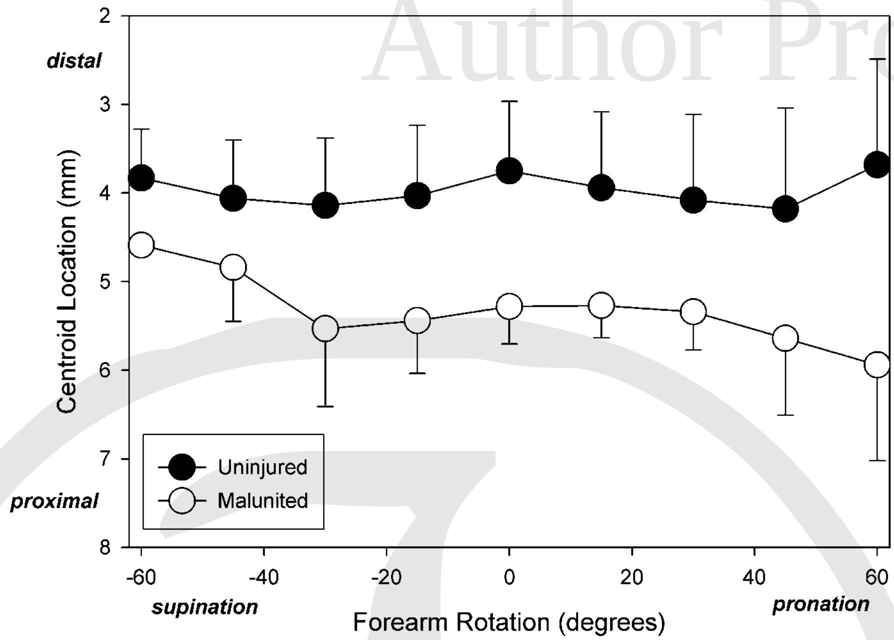

Figure 4. The centroid of the joint interbone distance area on the ulna (JSC) was located significantly ($p < 0.01$) more proximal in the malunited forearms at all forearm position (except 60° of supination where statistics were not run because of low sample size). The location of the JSC did not significantly vary with forearm supination-pronation motion in the uninjured writs, but tended to move more proximal in the malunited forearm.

manually active patients.[7] In our previous analysis of the nine patients in this study[12] we found that distal radius malunion did not alter the kinematic pattern of the radius during prono-supination, and that motion was not limited by bony constraints at the sigmoid notch. That study demonstrated that altered kinematics of the DRUJ was not the primary cause of distal radioulnar dysfunction. Accordingly, in the current study, we hypothesized that malunion of the distal radius might alter the mechanics of the DRUJ. We hypothesized that malunion would lead to changes in joint contact area or loading, which could ultimately affect long-term clinical outcome. Our data demonstrate that joint interbone space area at the DRUJ is significantly smaller and located more proximally in the wrists of patients with malunited distal radius fractures, and that the computed ligament path length for the dorsal radioulnar ligament is increased in these patients.

Joint incongruence and ulnocarpal abutment initiate irreversible cartilage damage that leads to degeneration of the DRUJ.[18] Although a definitive causal link has not yet been established, it is believed that changes in DRUJ mechanics may be involved. Although Bronstein et al.[10] reported that dorsal tilt to 30° *in a cadaver model*did not restrict forearm rotation, it is generally accepted that increasing dorsal tilt increases DRUJ incongruity, especially in cases where angulation exceeds 20° (or >10° dorsal tilt), and limits maximum pronation and supination,[9] as does radial shortening.[19] Isolated radial shortening, epiphyseal inclination and axial malunion reduce radioulnar contact at the DRUJ, which is exacerbated at the extremes of supination and pronation.[20] These studies are consistent with our findings, which indicate that distal radius malunion of $20.9 \pm 5.8°$ resulted in a significant reduction in joint spacing and a significant proximal shift in the location of the joint interbone space centroid.

Malunions are most frequently combinations of radial shortening, dorsal tilt, radial inclination and pronation. The deformities in our subjects included radial shortening (transverse plane), dorsal tilt of the distal radius joint surface (sagittal plane), and loss of radial inclination (coronal plane). Although it can be proposed that radial shortening alone would shift the center of contact of the DRUJ proximally on the ulna, dorsal tilt may also contribute to a proximal shift of the radioulnar joint center. The precise changes in DRUJ articular alignment that caused a proximal shift in the JSC in this study were not ascertained because the

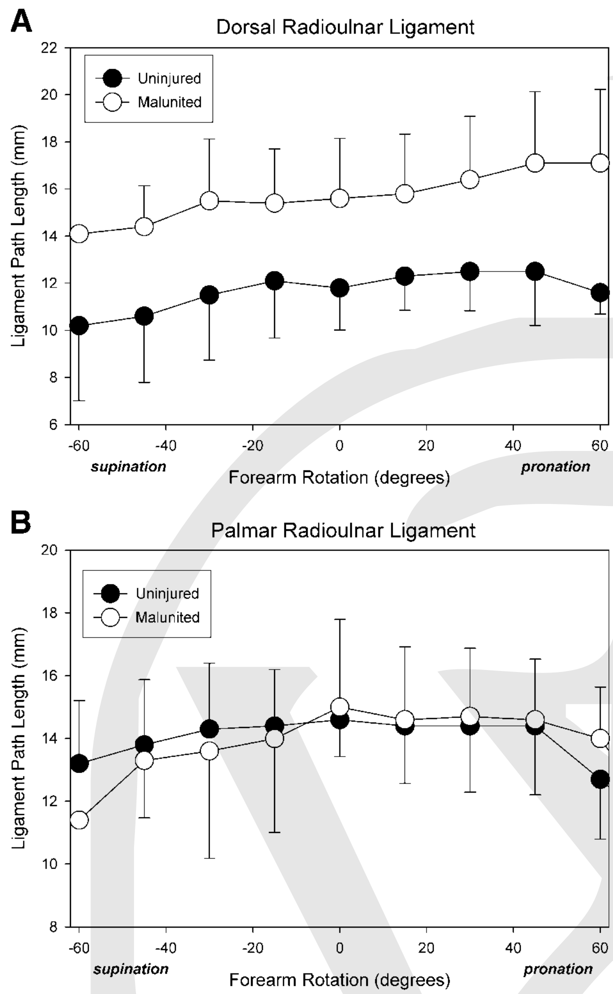

Figure 5. Malunion significantly ($p < 0.01$) increased computed dorsal radioulnar ligament path length (A) throughout forearm supination/pronation. In the uninjured forearms, we could not detect changes in the computed elongation of the dorsal radioulnar ligament with various forearm positions. The palmar radioulnar ligament tended to decrease its path length as the forearm rotated from neutral with pronation and with supination, but no differences with the malunited wrists could be detected (B).

contribution from each deformity was not isolated. A cadaver study could ideally examine each plane of deformity independently, but may have limited clinical applicability because of the complexity of the deformities that actually occur in vivo.

In normal forearms, laboratory studies reveal that DRUJ contact area is reduced at the extremes of pronation and supination.[21,22] Our results are consistent with these observations, but our analysis of forearm rotation did not include measurements beyond 60° of supination or pronation. Ishii et al.[23] reported the contact center to shift dorsally in pronation, and palmar in supination in the uninjured DRUJ, which is in contrast to our finding of no appreciable shift during normal forearm rotation.

We found the computed path length of the dorsal radioulnar ligament increased with malunion, and that in many positions the dorsal radioulnar ligament was forced to wrap over the head of the ulna. These findings lend support to the concept that soft tissues rather than bony impingement likely limit forearm rotation in certain patients with malunited distal radius fractures. Although we found significant differences in the elongation of the radioulnar ligaments, it should be emphasized that these measurements do not provide an indication of the load in the ligament or the resting tension on the ligament. One may speculate that the load in the dorsal ligament was increased due to its increased length with malunion, but it is possible that the ligament may have torn and/or undergone some remodeling after injury, which would have influenced the stress within the ligament. In cadaver studies using direct tension measurements,[24] kinematic measures,[11,25,26] and gross anatomical observations,[27,28] the palmar ligament has been reported to be tensioned (lengthened) more than the dorsal ligament in supination, whereas the dorsal was tensioned (lengthened) more than the palmar in pronation. However, this description of the role of the radioulnar ligaments is not consistent with the observations of af Ekenstam and Hagert.[21] We found that the computed path lengths for the dorsal radioulnar ligament in the uninjured forearm tended to elongate with pronation. The computed path lengths for palmar radioulnar ligaments in our study tended to be longest in the neutral posture, suggesting it tightened it supination and pronation. Our conclusions on the behavior of the intact ligaments are limited because the full ROM of forearm rotation could not be studied.

In this study we developed techniques to quantify in vivo changes in joint mechanics. There are limitations in these techniques and in our study. First, extrapolation of our findings beyond this subject population should be done with care. The nine patients in our study had clinically significant malunions, but did not have severe functional limitations. It is unknown if the findings of this study, as well as those of our previous study, would be applicable to patients with more severe malunions and more pronounced functional limitations. Second, the accuracy of our measurements depends on the accuracy of the segmentation, registration, and joint modeling algorithms. The kinematic error inherent in our techniques for the radius, which include the segmentation and registration algorithms, have been determined to be less than $0.2 \pm 0.3^\circ$ and 0.2 ± 0.1 mm.[29] Third, our joint space area variable (JSA) is not a direct measure of articular contact area. We are limited in our ability to calculate cartilage contact using our current methodologies because cartilage is poorly imaged with CT. However, we have preliminary unpublished data that suggests there is a strong correlation between our measure of joint space area and cartilage contact area. Our findings are consistent with the fact that joint space narrowing is the only validated measure for clinically evaluating the progression of knee osteoarthritis in clinical studies.[30] At this point it is appropriate to consider our JSA as a 3D analog of the 2D measurements of joint space narrowing. Fourth, we limited our analysis to the interbone distance map on the surface of the ulna. We did this because the intact ulna provided a consistent coordinate system that facilitated comparison of the malunited and uninjured wrists. A corresponding distance map can be computed for the radius, but the distorted morphology in the malunited distal radiuses introduced more variability in the joint space measures. Finally, the ligament lengths that we calculated reflect the shortest paths between subjectively chosen insertion points, with the constraint that the path lies outside the bone surface models. These paths are subject to errors in the bone surface models and the estimated kinematics and may also not take into account additional anatomical constraints.

In conclusion, we used novel CT image-based methodology to quantify in vivo mechanics of the DRUJ in both wrists of nine patients with unilateral malunited distal radius fractures. Previously we found that during pronosupination the 3D kinematics of the radius relative to the ulna were not altered with malunion. In the current analysis we have documented that despite relatively normal kinematics, the mechanics of the DRUJ, quantified by ulna joint space area, centroid position, and the length of the dorsal radioulnar ligament, were significantly altered with malunion. It is possible that these changes, not changes in kinematics, may play a role in the development of early degenerative joint disease.

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