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Distal Radioulnar Joint Reaction Force Following Ulnar Shortening: Diaphyseal Osteotomy Versus Wafer Resection

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Abstract

Purpose—To compare how ulnar diaphyseal shortening and wafer resection affect distal radioulnar joint (DRUJ) joint reaction force (JRF) using a nondestructive method of measurement. Our hypothesis was that ulnar shortening osteotomy would increase DRUJ JRF more than wafer resection.

Methods—Eight fresh-frozen human cadaveric upper limbs were obtained. Under fluoroscopic guidance, a threaded pin was inserted into the lateral radius orthogonal to the DRUJ and a second pin was placed in the medial ulna coaxial to the radial pin. Each limb was mounted onto a mechanical tensile testing machine and a distracting force was applied across the DRUJ while force and displacement were simultaneously measured. Data sets were entered into a computer and a polynomial was generated and solved to determine the JRF. This process was repeated after ulnar diaphyseal osteotomy, ulnar re-lengthening, and ulnar wafer resection. The JRF was compared among the 4 conditions.

Results—Average baseline DRUJ JRF for the 8 arms increased significantly after diaphyseal ulnar shortening osteotomy (7.2 vs 10.3 N). Average JRF after re-lengthening the ulna and wafer resection was 6.9 and 6.7 N, respectively. There were no differences in JRF among baseline, relengthened, and wafer resection conditions.

Conclusions—Distal radioulnar joint JRF increased significantly after ulnar diaphyseal shortening osteotomy and did not increase after ulnar wafer resection.

Clinical relevance—Diaphyseal ulnar shortening osteotomy increases DRUJ JRF, which may lead to DRUJ arthrosis.

Keywords

Ulnar shortening; distal radioulnar joint; joint reaction force; wrist

Ulnar shortening osteotomy is a common, effective procedure for treating ulnar impaction syndrome.^{1,2} Biomechanical studies have demonstrated that surgical shortening of the ulna decreases loads across the ulnocarpal joint³ and stabilizes the distal radioulnar joint (DRUJ).^{4,5} However, biomechanical data also demonstrate that ulnar shortening results in increased DRUJ pressure.⁶ Although enhanced DRUJ stability may be desirable in some cases, increased pressure within the DRUJ has the potential to lead to pain and DRUJ arthrosis. Radiographic changes within the DRUJ have been observed after ulnar shortening procedures.^{7,8} Such changes may be a result of increased forces across the DRUJ resulting from ulnar shortening.

Ulnar shortening is most commonly accomplished by performing a diaphyseal shortening osteotomy^{2,9,10} or a distal ulnar wafer resection.¹¹ Little is known about how the location of the osteotomy affects DRUJ joint reaction force (JRF). In a biomechanical study comparing ulnar osteotomies proximal and distal to the distal interosseous membrane, Arimitsu et al⁴ found that proximal osteotomy resulted in significantly greater DRUJ stability. However, the effects on DRUJ JRF were not measured. Because increased JRF across the DRUJ may lead to subsequent arthrosis and pain, it is important to determine how the location of the osteotomy might affect JRF.

Prior biomechanical studies have examined pressure across the DRUJ using pressure-sensitive devices inserted into the joint.^{6,12,13} Such techniques require dissection around the joint, removal of stabilizing soft tissue structures, and a capsulotomy for insertion of the pressure sensor. Sectioning of these structures has been shown to alter DRUJ stability,¹⁴ and there are concerns about the reliability of measurements using devices interposed between articular surfaces.^{15,16}

The reaction force experienced at a joint is a sum of the forces acting on that joint, including the effect of gravity on the mass of the limb, muscle forces, and tension within the soft tissues across the joint. These forces tend to compress the joint, and in response the articular surfaces experience equal, opposing JRFs that resist this compression. The purpose of the current study was to compare how ulnar diaphyseal shortening and distal ulnar wafer resection affect DRUJ JRF. Our hypothesis was that ulnar shortening would increase DRUJ JRF and diaphyseal shortening osteotomy would increase DRUJ JRF more than wafer resection.

MATERIALS AND METHODS

In prior work, we developed a reliable, nondestructive method of measuring DRUJ JRF that preserves all soft tissues about the DRUJ and does not require insertion of a device into the joint.¹⁸ This method involves distracting the joint to the point where the distraction force is equal and opposite to the baseline compressive force. The details and theory behind this method have been previously described.^{18,19} Based on a pilot study measuring DRUJ JRF

with this technique in 7 specimens, a power analysis demonstrated a sample size of 7 would have 83% power to detect a 30% increase in JRF with a significance level of .05 using a 2-sided paired t test. Therefore, 8 fresh-frozen human cadaveric upper limbs from the shoulder girdle to the hand were obtained. All specimens were physically and radiographically examined to rule out preexisting DRUJ pathology and previous fracture or surgery in the upper extremity. We classified DRUJ orientations according to the Tolat system²⁰ (type 1, parallel; type 2, oblique; type 3, reverse oblique). Specimens were excluded if they had a Tolat type 3 DRUJ or greater than 1 mm positive or negative ulnar variance.

Under fluoroscopic guidance, a threaded Steinmann pin was placed in the middle of the lateral side of the distal radius transverse to the DRUJ. A second pin was placed in the middle of the medial side of the distal ulna colinear to the radial pin. Pins were placed percutaneously, preserving all soft tissue about the DRUJ.

Specimens were mounted onto a tensile testing machine (MTS Insight 100; MTS Systems, Eden Prairie, MN) using a custom fixture with the elbow fixed at 90° and the forearm in neutral rotation (Fig. 1). An axial extensometer (MTS 634.28; MTS Systems) was placed on each pin to allow for precise measurement of displacement. A uniaxial distracting force was applied across the DRUJ at a rate of 0.4 mm/s while force and displacement were simultaneously and constantly measured. We chose this relatively slow rate of distraction to minimize the viscoelastic effects of the soft tissues. Force displacement curves were generated for each arm and a best-fit polynomial function was calculated to model the curve. The second derivative of the polynomial was set to 0 and its root was solved to determine the inflection point representing JRF. The details of this method of JRF measurement have been previously described.¹⁸ Each measurement was performed 3 times and the average of the 3 measurements was used.

After we obtained baseline control data, we performed a standard ulnar diaphyseal shortening osteotomy with resection of a 3-mm segment at a location 6 cm proximal to the ulnar styloid. The amount of ulna to be resected was measured with calipers before performing the osteotomy. Osteotomies were fixed with a custom-slotted, 3.5-mm dynamic compression plate to allow subsequent re-lengthening of the ulna (Synthes, West Chester, PA). Joint reaction force was measured as described above. The ulnas were then re-lengthened by 3 mm, measured with precise calipers. The removed segment of bone was reinserted as a supplementary method to confirm that the original length was reestablished. The ulnas were held at their original length using the custom compression plate (Fig. 2). The ulnas were re-lengthened to reestablish normal anatomy and return JRF to baseline before performing wafer resection. This allowed each specimen to serve as its own control and verify that changes in JRF from ulnar shortening could be reversed with re-lengthening. Joint reaction force was calculated in the relengthened state to confirm return to baseline. We then performed a distal ulna wafer resection with removal of a 3 mm wafer as described by Feldon et al¹¹ and again calculated JRF. Care was taken to protect the triangular fibrocartilage complex (TFCC), which was grossly intact in all specimens, and the dorsal wrist capsule was repaired after wafer resection.

Comparisons of JRF among the 4 conditions (baseline, diaphyseal shortening, re-lengthened, and wafer resection) were performed using a linear mixed model with the conditions as the covariate. The unit of observation was the limb under each condition, and a Bonferroni correction was performed to adjust for multiple comparisons. The intraclass correlation coefficient was calculated to determine reliability of repeated measurements and to make sure the distraction force applied did not result in deformation of soft tissues and alteration of JRF.

RESULTS

The intraclass correlation coefficient for reliability of repeated measurements was 0.98, confirming high repeatability between consecutive measurements on each specimen.

Average baseline DRUJ JRF was 7.2 ± 2.5 N (range, 3.5–11.0 N). Diaphyseal ulnar shortening osteotomy resulted in a statistically significant increase in DRUJ JRF compared with baseline (10.3 ± 3.3 N; $P = .002$). In contrast, wafer resection did not significantly alter DRUJ JRF (6.7 ± 1.9 N; $P = .990$). Figure 3 shows a representative force–displacement curve demonstrating the 4 conditions tested.

Compared with baseline DRUJ JRF, re-lengthening the ulna resulted in a slight decrease in JRF that was not significant (6.9 ± 2.2 N; $P = .990$). Compared with the re-lengthened ulnas, there was no difference in JRF after wafer resection (6.9 and 6.7 N, respectively; $P = .990$).

DISCUSSION

Surgical shortening of the ulna is a well-established method of treating ulnar impaction syndrome. Diaphyseal osteotomy is the reference standard and has proven effective in improving symptoms resulting from ulnar impaction syndrome.^{1,2,21} However, diaphyseal osteotomy alters the biomechanics of the DRUJ, which could lead to arthrosis. Deshmukh et al²² demonstrated that shortening of the ulna by 2 mm resulted in DRUJ articular incongruity and Nishiwaki et al⁶ demonstrated that ulnar shortening increased pressure at the DRUJ. Furthermore, clinical studies have shown radiographic changes within the DRUJ in 16% to 50% of patients within an average of 18 to 60 months after ulnar shortening procedures.^{7,8,21,25} The current study demonstrated that diaphyseal ulnar shortening osteotomy significantly increased transverse DRUJ JRF, whereas distal ulna wafer resection does not affect JRF.

The mechanism by which diaphyseal ulnar shortening increased DRUJ JRF likely involves increased tension within the soft tissues surrounding the DRUJ. In their biomechanical study evaluating the effect of ulnar shortening on DRUJ stability, Nishiwaki et al⁵ demonstrated that increased DRUJ stability resulted from increased tension in the TFCC. In a follow-up study, they also demonstrated increased pressure in the DRUJ after ulnar shortening.⁶ Arimitsu et al⁴ compared DRUJ stability after ulnar shortening proximal and distal to the distal interosseous membrane. They found that stability was greater after proximal shortening. They concluded that the stabilizing mechanism involved increased tension within the distal interosseous membrane that occurred only with the proximal osteotomy. The current study demonstrated that proximal ulnar diaphyseal osteotomy increased DRUJ

JRF but distal wafer resection did not. We believe this supports the findings of Arimitsu et al. Increased tension within soft tissues about the DRUJ that occurs after diaphyseal osteotomy likely results in both increased DRUJ stability and increased DRUJ JRF.

The primary clinical relevance of increasing DRUJ JRF is that it directly results in elevated contact pressures at the articular surfaces. This occurs because contact pressure (P) is equal to the reaction force (F) divided by the surface area (A) over which the force is distributed ($P = F/A$).¹⁷ Therefore, P increases when F is increased and/or surface area is decreased. In the current study we demonstrated that ulnar shortening results in increased force transmission across the DRUJ. However, ulnar shortening osteotomy also alters the congruity of the DRUJ (affecting surface area) and therefore results in altered pressure distributions across the joint.²² This can lead to decreased contact areas and result in regions subjected to peak pressures much higher than they would be in a congruous joint. Some ulnar-positive wrists may have incongruent DRUJs at baseline, and ulnar shortening may potentially increase joint congruity (which would be expected to decrease contact pressures). However, wrists with congruent DRUJs at baseline have this congruity altered after ulnar shortening, resulting in areas of increased contact pressures. Therefore, methods of mapping pressure distribution across the DRUJ are also important. However, directly measuring pressure in the DRUJ is problematic because it requires insertion of a pressure-sensing device into the joint. Such devices cannot perfectly conform to the articular surfaces, and studies evaluating the accuracy of pressure-sensing films suggest measurement errors ranging in magnitudes of 14% to 77%.^{16,23} The current study sought to determine how ulnar shortening affects force distribution across the DRUJ. This evaluated only how the force variable affects DRUJ pressure, and we were therefore unable to make conclusions about how altered joint congruity affects DRUJ pressure. However, others have investigated this.⁶

Increasing JRF at the DRUJ could cause pain because of elevated joint contact pressures. Although this phenomenon has not been widely appreciated in the DRUJ, it has been described in other joints, notably in the knee where increased patellofemoral JRF can cause anterior knee pain.²⁴ Persistently elevated joint contact pressures could also lead to joint degeneration. Several authors^{7,8,21,25} have reported degenerative changes at the DRUJ after ulnar shortening osteotomy, with incidences of 16% to 50%. These changes were observed at 2 to 5 years' follow-up and were not associated with symptoms. However, Sagerman et al²⁶ reported a case of symptomatic DRUJ arthrosis after ulnar shortening osteotomy. The reason these changes develop is likely because of a combination of increased forces acting across the DRUJ and decreased articular congruity resulting from ulnar shortening. Although the incidence of radiographic changes occurring relatively soon after ulnar shortening is concerning, it remains unclear how many of these patients develop symptoms.

Distal ulnar wafer resection may represent an attractive alternative method of shortening the ulna because it does not result in increased tension of the soft tissues about the DRUJ and does not increase JRF. Both wafer resection and diaphyseal osteotomy have been shown to decrease loads across the ulnocarpal joint.^{27,28} A recent systematic review demonstrated favorable outcomes after open wafer resection.²⁹ However, Lapner et al³⁰ reported 2 cases of early osteoarthritis after wafer resection. They also demonstrated that wafer resection resulted in increased DRUJ pressure. This can be explained by the fact that although forces

across the DRUJ do not change after wafer resection, the joint contact area decreases, and as a result, pressure increases. Further studies are required to determine whether there are different rates in DRUJ arthrosis after diaphyseal osteotomy and wafer resection.

There are theoretical differences that may differentiate the effects of diaphyseal ulnar shortening osteotomy and wafer resection on the carpus. Ulnar shortening osteotomy maintains the bony underpinnings and support for the TFCC whereas the wafer osteotomy does not. The removal of cartilage on the end of the ulna may leave the carpus with less overall columnar support but it may also contribute further to the relief of ulnocarpal impaction. If there is no bone under the TFCC, there is even less of a source of pressure on the carpus. However, this gain may be diminished by the loss of smooth gliding of the ulna beneath the TFCC afforded by maintenance of the normal distal ulnar cartilaginous surface.

The risk of DRUJ arthrosis after ulnar shortening might be decreased by performing a distal metaphyseal osteotomy instead of a standard diaphyseal osteotomy. This technique is gaining in popularity primarily because it theoretically reduces the risk of nonunion and symptomatic hardware is less likely.^{31,32} In addition, by moving the osteotomy site distal to the distal portion of the interosseous membrane, the increased soft tissue tension that leads to increased force across the DRUJ may also be avoided. In a recent study examining the biomechanics of the distal metaphyseal ulnar shortening osteotomy, Greenberg et al³³ demonstrated that this osteotomy does not increase transverse DRUJ JRF. However, it remains to be seen whether maintenance of normal joint reaction forces across the DRUJ after distal metaphyseal ulnar shortening osteotomy results in decreased rates of degenerative changes.

A strength of our current study is that it employed a method of measuring DRUJ JRF that preserved all soft tissues about the wrist to demonstrate that diaphyseal ulnar osteotomy increases DRUJ JRF and wafer resection does not. Prior methods of measuring forces acting across the DRUJ have required arthrotomy and insertion of pressure-sensitive films and devices into the joint.^{3,6,12,13,30,33,34} Violation of the stabilizing soft tissues about the wrist alters normal biomechanics and may confound measurements of forces acting across the wrist. In addition, it is challenging to obtain an accurate assessment of true pressure when these devices are inserted into joints.¹⁶ We believe our technique, which has been described previously,¹⁸ circumvents these problems.

This study has several limitations. To obtain a uniform sample and minimize variability, we excluded wrists with more than 1 mm positive or negative ulnar variance, and we performed 3 mm shortening on all specimens. Ulnar shortening is typically performed on ulnar-positive wrists and the amount of shortening performed is based on the degree of ulnar positivity. The effect ulnar shortening has on DRUJ JRF in wrists that are ulnar positive could differ from that which we found in relatively neutral wrists. Forearm rotation has been shown to affect DRUJ JRF.³⁴ The technique we described to measure JRF is unable to accommodate measuring JRF in different degrees of pronosupination, and therefore all of our observations were made with the forearm in neutral rotation. We were also able to measure only resting JRF and were unable to assess dynamically how JRF changes when the forearm muscles were loaded. Because DRUJ reaction forces increase substantially with loading of the

muscles in the upper extremity,³⁵ we can only extrapolate from our data that ulnar shortening increases DRUJ in the loaded state as well. However, because we were unable to measure the effect of dynamic forces on DRUJ JRF after ulnar shortening, we cannot conclude that this is true. Finally, although statistically significant, the clinical importance of the small absolute increase in resting DRUJ JRF found in this study is uncertain.

Standard ulnar diaphyseal osteotomy results in increased resting DRUJ JRF. Although this may offer a joint stabilizing effect, it could also result in pain and the development of arthrosis owing to increased contact pressures. Wafer resection does not alter DRUJ JRF, but previous work demonstrates that it increases DRUJ pressure by decreasing joint contact area.³⁰ Therefore, both techniques could contribute to the development of DRUJ arthrosis. Distal metaphyseal ulnar shortening osteotomy may theoretically decrease the risk of DRUJ arthrosis because it does not decrease DRUJ contact area and does not increase DRUJ JRF.³³ However, additional clinical studies with long-term follow-up are required to determine whether these biomechanical advantages result in decreased rates of DRUJ arthrosis and superior clinical outcomes.

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FIGURE 1.
Experimental setup with equipment labeled.

FIGURE 2. Fluoroscopic images showing ulna A at baseline length, B shortened, and C re-lengthened to original length.

FIGURE 3.

Representative force–displacement curves used to calculate JRF (the force value at the first inflection point) for a single specimen. Diaphyseal shortening resulted in significantly higher JRF. This represents one single representative specimen and not the averages for all specimens.