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A Nondestructive, Reproducible Method of Measuring Joint Reaction Force at the Distal Radioulnar Joint

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Abstract

Purpose—To develop a nondestructive method of measuring distal radioulnar joint (DRUJ) joint reaction force (JRF) that preserves all periarticular soft tissues and more accurately reflects in vivo conditions.

Methods—Eight fresh-frozen human cadaveric limbs were obtained. 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 into the middle of the medial side of the distal ulna colinear to the distal radial pin. Specimens were mounted onto a tensile testing machine using a custom fixture. A uniaxial distracting force was applied across the DRUJ while force and displacement were simultaneously measured. Force-displacement curves were generated and a best-fit polynomial was solved to determine JRF.

Results—All force-displacement curves demonstrated an initial high slope where relatively large forces were required to distract the joint. This ended with an inflection point followed by a linear area with a low slope, where small increases in force generated larger amounts of distraction. Each sample was measured 3 times and there was high reproducibility between repeated measurements. The average baseline DRUJ JRF was 7.5 N (n = 8).

Conclusions—This study describes a reproducible method of measuring DRUJ reaction forces that preserves all periarticular stabilizing structures. This technique of JRF measurement may also be suited for applications in the small joints of the wrist and hand.

Clinical relevance—Changes in JRF can alter native joint mechanics and lead to pathology. Reliable methods of measuring these forces are important for determining how pathology and surgical interventions affect joint biomechanics.

Keywords

Biomechanics; distal radioulnar joint; joint reaction force; wrist

The distal radioulnar joint (DRUJ) is complex and is commonly implicated in wrist pathology and disability.^{1–4} Fractures of the distal radius and direct injury to the DRUJ can

cause altered mechanics that can lead to arthrosis.⁴⁻⁶ Joint leveling procedures can also cause increased pressure within the DRUJ.^{7,8} Increased joint contact forces are likely a contributing factor in the development of DRUJ arthrosis. Accurate means of measuring such forces has clinical relevance but is technically challenging.

Numerous biomechanical studies have measured contact pressures in the DRUJ.⁷⁻¹² The methods employed relied on destructive techniques including obligate arthrotomy and insertion of pressure sensors or films into the sigmoid notch. The periarticular soft tissue dissection required in these studies altered the normal mechanics of the DRUJ.^{13,14}

Much has been written about the anatomical contributions to DRUJ stability and the importance of its soft tissue stabilizers.^{3,15-21} Prior work shows that the soft tissue restraints about the DRUJ confer approximately 80% of DRUJ stability, whereas the bony articulation between the ulnar head and the sigmoid notch is responsible for 20%.¹⁷ Therefore, invasive methods of measuring pressure and force across the DRUJ that involve arthrotomy and disruption of the periarticular soft tissues for intra-articular device insertion likely destabilize the joint and alter native joint forces. In addition, placement of a device between 2 conforming articular surfaces has been shown to disrupt normal joint mechanics.²²⁻²⁴ Therefore, the potential for measurement inaccuracy using these techniques is a concern.

In order for a joint to be in static equilibrium, the sum of all forces acting across that joint must be zero. The forces contributed by the mass of the limb/gravity, muscle, and tension within the soft tissues across the joint act to compress the articular surfaces together. The articular surfaces experience equal, opposing joint reaction forces (JRF) that resist this compression. These forces result in compressive deformation of the articular surfaces.²⁵ Yang et al²⁶ described a method of measuring JRF in the knee by simultaneously applying a joint distracting force and measuring joint displacement. As the distracting force was applied, a point was reached just before the surfaces separated when the compressive forces were overcome and the surfaces were no longer compressed but were not yet distracted. When the distracting force was plotted against joint displacement, a measurable inflection point on the curve represented this point. At this point, the distracting force applied was equal and opposite to the compressive forces acting across the joint. In their work on a knee model, Yang et al²⁶ demonstrated that this force was equivalent to the JRF. We sought to develop a similar model to measure JRF in the DRUJ. We reasoned that such an approach would be particularly well suited to the smaller joints of the hand and wrist, where significant disruption of the supporting soft tissues could be avoided using this technique.

The purpose of this study was to develop a non-destructive method of measuring transverse JRF across the DRUJ. We hypothesized that reproducible, accurate measures of DRUJ JRF are possible without disrupting the joint.

METHODS

Specimen preparation

Eight fresh-frozen cadaver upper limbs were obtained through standard institutional protocols. Each limb was physically examined to rule out gross DRUJ laxity. Each specimen

was radiographically evaluated to assess for preexisting DRUJ pathology. Extremities that demonstrated evidence of significant DRUJ pathology or laxity were excluded.

Under fluoroscopic guidance, a threaded Steinmann pin was placed in the middle of the lateral side of the distal radius, directly across from, and transverse to, the DRUJ. On its nonthreaded end, the pin was custom-machined to thread onto a tensile load cell (Futek, Irvine, CA). A second pin was placed in the middle of the medial side of the distal ulna colinear to the distal radial pin (Fig. 1). All pins were placed percutaneously, leaving the soft tissues of the wrist intact.

The specimens were then mounted onto a tensile testing machine (MTS Insight 100, MTS Systems, Eden Prairie, MN) using a custom fixation apparatus with the elbow at 90° and the forearm held in neutral rotation with the ulna fixed to the apparatus (Fig. 2). A precalibrated axial extensometer (MTS 634.28, MTS Systems, Eden Prairie, MN) was placed on each pin to allow for precise measurement of displacement. Because displacement of less than 1 mm cannot be reliably detected radiographically, fluoroscopy was not used to measure distraction.²⁷ A uniaxial distracting force was then applied transversely across the DRUJ using the tensile load cell while force and displacement were simultaneously and constantly measured. The radius was pulled away from the fixed ulna (Fig. 2). The DRUJ was distracted 0.25 mm at a rate of 0.4 mm/s. The distance of 0.25 mm distraction was found to be sufficient to reach the inflection point in pilot testing. Each measurement was performed 3 times and the average of the 3 measurements was used to determine JRF. In order to allow soft tissues to return to their original lengths, 2 minutes was allowed for soft tissue relaxation between measurements. This was a sufficient amount of time to allow the extensometer to return to zero, indicating return to baseline soft tissue length. Because this study was performed on cadavers, JRF in this paper was defined as the capsular and soft tissue tension across the joint. This tension does not include dynamic muscular forces and, therefore, models an unloaded joint.

Calculation of JRF

The data sets for the force-displacement curves were entered into a computer and a best-fit polynomial was generated to fit the force-displacement curve. To precisely determine the inflection point representing the JRF, the second derivative of this polynomial was set to zero and its root was solved to determine the inflection point. This allowed for a more precise determination of the inflection point than would be obtained by visually estimating it on the force-displacement graph.

Statistical analysis

Mean and SD for JRF among the specimens were calculated. To measure the reliability of this method of measuring JRF and to confirm that distraction did not result in permanent deformation of the soft tissues, each measurement was performed 3 times and the intraclass correlation coefficient (ICC) was calculated. The coefficient of determination (R²) was calculated for the equation of the best-fit line used to calculate the inflection point for each data set. All statistical calculations were performed in conjunction with a university biostatistician.

RESULTS

A representative figure depicting the inflection point on the force-displacement curve is shown in Figure 3. Each curve demonstrated an initial high slope phase where relatively large amounts of force were required to distract the joint. This ended with an inflection point followed by a linear phase with a much lower slope where relatively small amounts of force were required for joint distraction. This is in accordance with the theoretical considerations described by Yang et al²⁶ regarding this technique of measuring JRF.

The average R² value for the best-fit curves for the data sets was greater than 0.99, indicating a high degree of conformity between the empirical data and the model used to fit the data sets. The polynomial for this function that was solved to determine the JRF is also demonstrated. The ICC for the repeated measurements of JRF was 0.98, indicating a high degree of measurement reliability (Fig. 4). Mean JRF for all specimens was 7.5 N (3.5 N–11.0 N). The SD of the mean JRF for the 7 specimens was 2.5 N, indicating a high degree of interspecimen variability.

DISCUSSION

The forces acting across joints play important roles in determining joint stability and may contribute to pathology when altered beyond physiological norms. Reliable techniques for measuring these forces are therefore desirable, and when pathology is a consequence of these forces, accurate measurement becomes critical. Ideally, measurements should be obtained using nondestructive techniques to preserve normal joint mechanics and obtain values that reflect those in vivo as closely as possible. Nowhere is this more relevant than in small joints where the soft tissues are often critical stabilizers, and once violated, clinical relevance is sacrificed.

The present study adapted a method of determining DRUJ JRF by applying a distracting force across the DRUJ and constantly measuring the amount of force applied and the distance the joint was distracted. This technique and its validity have been described by Yang et al²⁶ for a knee model. The applicability of this technique to small joints is important, because other means of measuring JRF are particularly destructive to these joints.

The force-displacement curves we found for the DRUJ had similar characteristics to those previously found with the knee.²⁶ In contrast to Yang et al,²⁶ we were able to simultaneously and constantly measure force and displacement. This generated over 100 data points for each trial and allowed for a precise measurement of JRF. This is reflected in the average R² value of greater than 0.99 for the best-fit curves for the data sets.

Several authors have measured pressure and force across the DRUJ.^{7–11,13,14,28} However, prior methods have all involved major disruptions of periarticular soft tissues, which likely altered normal joint mechanics. In addition, methods that involve capsulotomy for sensor insertion result in loss of negative intra-articular pressure and its stabilizing suction effect. Although the role negative intra-articular pressure plays imparting DRUJ stability has not been reported, its importance in maintaining hip and shoulder stability is well documented.^{29,30} Our method may be uniquely suited to application in small joints such as the DRUJ

where forces at the articular surface may be greatly altered by periarticular dissection and interposition of pressure- sensing devices.

The average JRF measured in this study was 7.5 N. Greenberg et al¹³ measured DRUJ JRF using load cells and reported an average DRUJ JRF of 3.2 N at rest. This value is lower than that which we found. However, their method included sectioning of the distal interosseous membrane, which is an important structure that maintains DRUJ stability.^{16,19,21,31} Our measurements were performed with all soft tissues intact, including the interosseous membrane, which likely explains why our value was higher. Gordon et al¹⁴ used an instrumented distal ulna prosthesis to measure DRUJ JRF in a cadaver model. They did not report DRUJ JRF in an unloaded scenario but measured it at 0.6 N with a 20-N load through the pronator quadratus.¹⁴ The average resting value we found (7.5 N) is substantially higher than that found by Gordon et al¹⁴ even in some loaded states. We believe this is because the method of Gordon et al¹⁴ required removal of the entire distal ulna, which compromised DRUJ stability due to loss of DRUJ soft tissue stabilizers and release of the stabilizing suction effect of negative intra-articular pressure.

Nishiwaki et al⁸ also measured force across the DRUJ using a thin malleable pressure sensor and found an average DRUJ resting JRF of 0.1 N. This is markedly lower than values found in the current study and those by Greenberg et al¹³ and Gordon et al.¹⁴ In order to insert the sensors, Nishiwaki et al⁸ removed the capsule of the DRUJ and the distal membranous portions of the interosseous membrane; this may explain why their finding was so much lower than others.

To assess the reproducibility of the measurements in our study, each measurement was performed 3 times, and reliability was assessed by determining the ICC, which was 0.98 and established that, within any given specimen, our measurements were highly reliable. This is in accordance with Ito et al³² who used a similar technique to assess hip stability in distraction and reported an ICC of 0.99 for their measurements. This level of repeatability suggests that the testing process does not greatly weaken or deform the peri-articular stabilizing structures and lends validity to repeating measurements on the same specimens, as may be done to measure the effects of various surgical interventions.

Although intraspecimen variability was low, there was significant interspecimen variability. The large range of JRF (3.5 N–11.0 N) and high SD indicate a high degree of variability in JRF among specimens. Other authors who have measured joint forces also reported significant variability between specimens.^{26,32} Such variability is not unexpected because specimens vary by size, age, and sex in all series. There is likely a high degree of DRUJ JRF variability in vivo because there is considerable variability throughout the population in size, muscle bulk, and soft tissue properties, all of which would be expected to affect JRF.

In this study, we sought to establish a nondestructive method of measuring DRUJ JRF that was more accurate than previous methods that required joint disruption. In so doing, we aimed to better define the normal value of DRUJ JRF. To accomplish this, we excluded any specimens that showed physical or radiographic signs of DRUJ pathology. Therefore, we cannot suggest what values of DRUJ JRF may be associated with DRUJ arthrosis. However,

we believe they are higher than the average value seen in this study (7.5 N). The fact that our average value was higher than other previously reported values using invasive techniques (range, 0.1 N–3.2 N)^{8,13,14} supports the theory that dissecting the supporting soft tissues around the DRUJ results in a decrease in JRF. We believe our technique may allow for a more accurate assessment of DRUJ JRF in cadaver models and could offer a valuable method of assessing how various interventions or pathologies affect DRUJ JRF.

This study has several limitations. Forearm rotation has been shown to alter stability and pressure across the DRUJ.^{8,11,16,33} The technique described here was unable to facilitate an assessment of JRF in pronation/supination. Owing to technical constraints and equipment limitations, we were unable to measure JRF with simulated loading of the forearm muscles. However, other authors have demonstrated that loading the forearm muscles increases force across the DRUJ.^{8,14} In addition, whereas this technique is well suited to the DRUJ, it could be challenging to apply to other wrist joints that have multiple articulations and planes of motion. Finally, this study had all the limitations inherent in using a cadaver model to simulate living tissue. The forces present in the cadaver model were likely altered by changes in soft tissue elasticity and lack of muscle tone and may therefore not reflect values in vivo.

Further refinements to our technique that would allow for measuring JRF in various forearm positions and with simulated forearm muscle loading are needed. We believe that this method of minimally invasive measurement may be uniquely suited for evaluation of small joints of the upper extremity.

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FIGURE 1.
Fluoroscopic image of radial and ulnar pins placed coaxially in the transverse plane of the DRUJ.

FIGURE 2.
Drawing of the experimental setup demonstrates a specimen mounted on the tensile testing machine.

FIGURE 3.

A representative force-displacement curve shows its 3 phases. There is an initial high slope phase where the joint is compressed, followed by an inflection point where the joint surfaces are no longer compressed but have not yet separated. During the third, linear phase, the joint surfaces are distracting. The inflection point indicates the JRF, which in this example is 11.0 N. The R2 value for the best-fit line used to calculate the JRF was greater than 0.99.

FIGURE 4.

Graph depicts the reliability of repeated measurements. The intraclass correlation coefficient of measurement reliability was 0.98.