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Relative Contributions of the Midcarpal and Radiocarpal Joints to Dart Throwers' Motion at the Wrist

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Abstract

Purpose—To identify the relative contributions of the radiocarpal (RC) and midcarpal (MC) joints to Dart Thrower's Motion (DTM) of the wrist.

Methods—Six cadaveric upper extremities were fixed to a custom-designed loading jig allowing for pure moment-rotation analysis in 24 different directions of wrist motion. Each specimen was tested in three states: intact, simulated radiocarpal fusion (sRCF) and simulated pan-carpal fusion (sPCF). Moments of ± 1.5 Nm were applied at each of 24 directions for each state and the resulting wrist rotation recorded. Data from each specimen was reduced to compute the range-of-motion (ROM) envelopes and the orientation of the ROM for the three different states.

Results—ROM was significantly decreased in the sRCF and sPCF groups compared to the intact group in the directions of the pure extension, radial extension, ulnar flexion and ulnar deviation. No significant difference in ROM was detected between the sRCF and sPCF groups in any direction. ROM envelopes for the intact, sRCF and sPCF groups were all oriented obliquely to the axis of pure wrist flexion-extension near a path of ulnar flexion-radial extension, consistent with prior report on DTM.

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Conclusions—Although both simulated fusion types decreased ROM compared to the intact wrist, the principal direction of wrist motion along the path of DTM was not significantly altered by simulated RCF or PCF.

Keywords

Dart-throwers'-motion; radiocarpal fusion; midcarpal joint; wrist biomechanics

Introduction

Wrist range of motion results from a combination of complex osseous articulations and intricate soft tissue constraints. Recent advances in our understanding of the complex motions of the wrist have shown that in neutral forearm position, the mechanical axes of the wrist are oriented obliquely to the anatomic axes, with the primary direction being consistent with an oblique path of motion from radial extension through ulnar flexion. This path, known as the dart thrower's motion (DTM), first described nearly thirty years ago by Palmer et al [1], is necessary for a variety of tasks, and has even been argued to provide a unique survival advantage for humans. [2]

Prior research has investigated the kinematics and functional motion of the wrist. Anatomic factors, including individual carpal bone anatomy [3, 4], muscular attachments [5] and intraosseous ligaments [4, 6] have all been studied. Recent in-vivo analysis of activities of daily living and unconstrained wrist motion have further confirmed the use of the DTM in hammering, throwing, drinking, pouring and twisting of a jar lid. [7] Multiple radiographic and cadaveric studies have attempted to elucidate the contribution of individual carpal bones to DTM. [8–10] However this research has been limited in identifying which joint articulations are specifically responsible for this mechanical axis of DTM.

Clarifying which joints contribute to the path of the DTM would provide valuable insight into the carpal mechanism driving wrist motion. Surgeons performing partial carpal fusions, therapists designing rehabilitation protocols and engineers designing total wrist arthroplasties are just a few examples of treatment areas which would benefit from an improved understanding of the wrist's functional anatomy. The aim of this study was to identify the contribution of the radiocarpal (RC) and midcarpal (MC) joints to wrist ROM and the mechanical axes of the wrist. Based on prior reports that have demonstrated preserved motion after radio-scapholunate (RSL) fusions, [6, 7] we hypothesized that simulated radiocarpal fusion (sRCF) would not affect the orientation of the mechanical axes, while simulated pan-carpal fusion (sPCF) would alter the orientation of the mechanical axes of the wrist.

Methods

After screening for gross anatomic abnormalities both by direct visual inspection and fluoroscopic imaging, six fresh-frozen upper extremity cadaver specimens (three matched pairs) with the intact humeri disarticulated from the glenohumeral joint were prepared for use in the study. Specimens were kept frozen at -20°C until approximately 12 hours prior to testing, when they were allowed to thaw at ambient temperature. The metacarpals were

disarticulated at the metacarpophalangeal joint and screws were placed in the metacarpals to provide an adequate base for potting. Care was taken to preserve all ligamentous attachments. Neutral forearm rotation was achieved by placing the humerus, forearm and palm flat on the dissecting table, with the elbow flexed to 90°. The position of neutral forearm rotation was then standardized under fluoroscopic examination by carefully supinating or pronating the forearm to maximize the distance between the radial and ulnar styloids on an anteroposterior view of the wrist. [11] Proximally, the radius and ulna were then pinned with two Kirschner wires to maintain neutral forearm rotation. After pinning, the specimens were transected between the Kirschner wires and the elbow, then potted in a urethane compound (Smooth-On Inc., Easton, PA) both proximally and distally. For each specimen, the extensor radialis longus and brevis, extensor carpi ulnaris, flexor carpi radialis, and flexor carpi ulnaris tendons were isolated, and each of these four tendon groups was whip-stitched and attached to a constant force spring (4.45 N each; McMaster-Carr P.C., Robbinsville, NJ), whose force value was consistent with the loads applied to study tendon excursion and gliding in cadaver studies by An. [12]. The specimens were then mounted to a previously described positioning jig, [11] (Figure 1) as follows: with the forearm fixed in neutral rotation, the distal aspect of the specimen was mounted to the torsion actuator of the jig while proximally, the specimen was mounted to a plate, which was in turn connected to low-friction linear slides that were positioned orthogonal to each other. These slides allowed the specimen to travel freely in the horizontal plane, providing an unconstrained application of the moments and allowing the wrist to rotate about its physiological axes. With this setup, the direction through which the wrist moved was a function of both the direction of the applied moment and the inherent wrist anatomy which allowed the wrist to follow a path of least resistance for each moment applied.

Moment was applied in 24 directions of wrist motion as a modified sinusoidal wave in angular displacement control to 1.5 Nm at a test frequency of 0.1 Hz via the torsion actuator. To apply moments in each direction, the specimen was rotated about the forearm axis, and the potting fixtures were locked to the jig in 15° increments. Four of the 24 positions were those defined by anatomic axes (pure extension, ulnar deviation, pure flexion, and radial deviation) oriented at 90° angles to each other. (black arrowed axes in Figure 2) Together with the remaining 20 directions spaced equally apart from adjacent directions by 15° increments, a full 360° of wrist circumduction was studied. The moment-rotation behavior was determined from 0 to 1.5 Nm with each of the 24 directions of wrist loading. Similar to our previous report, [11] specimens were cyclically loaded for nine cycles in each direction for mechanical preconditioning, and the loading portion of the tenth cycle was used in the data analysis. Data was collected digitally at a rate of 25Hz (Fast Track 8800, Instron Corp., Norwood, MA).

The ROM at each direction of wrist loading was defined as the rotation from neutral to a moment value of 1.5 Nm. The ROM envelope, based on mechanical engineering principles, was defined as the solid object created by connecting adjacent ROM values at each of the 24 directions, as plotted on a polar coordinate system. [11] To determine the orientation of the range of motion, the principal axes of the ROM envelopes were calculated for each specimen using previously detailed methods. [11] The final stiffness was defined as the value the slope of the moment–rotation curve from 1.0 to 1.5 Nm at each direction of loading.

Following initial testing for each direction in the intact state, specimens were randomly allocated 1:1 to the order in which simulated fusions were performed. In three specimens, 3.5 mm Steinmann pins were first placed in an oblique fashion across the carpal bones (Figure 3) simulating a pancarpal fusion (sPCF), the specimens were tested and data was collected. Next, the Steinmann pins were removed and then placed along the RC joint (sRCF) (Figure 4), specimens were again tested and data was recorded. In the second group of three specimens, sRCF was performed prior to sPCF. In all cases, care was taken during insertion and removal of Steinmann pins to minimize any trauma to adjacent tissues, and pins were grossly monitored for signs of bending throughout the experiments.

To determine if there were significant differences in ROM, direction of principal motion, and stiffness among groups, a repeated measures ANOVA testing with the Holm-Sidak method for post hoc analysis was performed on each outcome measure. A value of $P < 0.05$ was used to determine statistical significance. Based on our assumption that sRCF would have a similar orientation to DTM, while sPCF would have an orientation closer to pure flexion-extension, we used a previous study of DTM with an analogous setup [11] as the basis for our *a priori* power analysis. In that study, the authors reported a mean difference in the orientation of the DTM axis to pure anatomic flexion-extension of 27° with standard deviation of less than 5° . Assuming a normal distribution and an effect size of 1.0, it was determined that we would need a minimum of four wrists (two wrists treated with sRCF and two treated with sPCF) to detect a significant difference ($P < 0.05$) of $20^\circ \pm 5^\circ$ in orientation with 80% power ($\alpha = 0.05$, $\beta = 0.2$). Because each specimen would be tested with in both the sRCF and sPCF states, two specimens would be necessary to satisfy the power analysis. To account for additional variation, we elected to use six specimens, which was the same number tested in the previous study. [11]

Results

The mean ROM for intact specimens loaded in pure anatomic extension was significantly greater at $61.4 \pm 9.8^\circ$ compared to $23.9 \pm 17.8^\circ$ and $24.3 \pm 12.4^\circ$ for the sPCF and sRCF groups, respectively ($P < 0.05$). In pure anatomic flexion, mean ROM for intact specimens was $62.1 \pm 22.4^\circ$ compared to $48.4 \pm 16.3^\circ$ and $37.9 \pm 6.2^\circ$ for the sPCF and sRCF groups, respectively, although there were no significant differences between any of the three groups. ROM was significantly decreased ($P < 0.05$) in both simulated fusion groups as compared to intact specimens when loaded in the directions of 15° to radial extension, 15° to ulnar flexion, and ulnar deviation (Figure 5). No significant difference in ROM was detected between the sRCF and sPCF groups at any of the 24 directions of loading.

Orientation of the ROM envelopes did not differ significantly between the intact, sRCF and sPCF groups, which represented motion at the native wrist, MC joint, and RC joint, respectively. All three envelopes were oriented obliquely with respect to the anatomic direction of flexion-extension by the following angles: intact, $26.6^\circ \pm 4.4^\circ$; MC joint, $20.4^\circ \pm 4.3^\circ$; RC joint, $22.2^\circ \pm 8.6^\circ$ (Figure 6). Stiffness increased significantly from the intact (0.15 ± 0.04 Nm), to the sPCF (0.25 ± 0.07 Nm) and sRCF (0.29 ± 0.11 Nm) groups in extension ($P < 0.05$). No significant difference in stiffness between the three groups was observed in any other direction.

Discussion

Recent advances in carpal kinematics have provided evidence that the mechanical axes of the wrist are oriented obliquely to the anatomic axes, with the primary direction being consistent with a path along the DTM. [5, 11] However, this research has been limited in identifying which joint articulations are specifically responsible for this mechanism. We theorized that RCF would not affect the orientation of the mechanical axes, while PCF would alter the orientation of the mechanical axes of the wrist. This hypothesis is like prior theories and outcome studies reporting that motion remains along the DTM axis after radio-scapholunate fusions. [6, 7] However, our biomechanical testing illustrated no statistically significant difference in ROM between the two fusion groups. In addition, although we observed a decrease in ROM between the intact and simulated fusion groups, our biomechanical testing illustrated that both the RC and MC joints tend to closely follow the principal mechanical axis located along the path of DTM of the completely intact carpus. This may indicate that these two joint complexes have a synergistic relationship with regard to their contribution to the mechanical axis of the wrist. In addition, for reasons that remain unclear, stiffness was only found to be significantly different for the fusion groups in pure extension, despite our prior work which generally found stiffness to be inversely related to ROM. [11] One possible explanation for this discrepancy is that stiffness, which was previously defined as the slope of the moment–rotation curve between 1.5 and 2.0 Nm, [11] was defined in this study as the slope from 1.0 to 1.5 Nm, (the maximum moment was reduced by 0.5 Nm to decrease the likelihood of micromotion at the simulated fusion interfaces).

These findings challenge prior understanding of wrist motion. Multiple theories have been proposed to explain wrist motion. In the early 20th century, Navarro first introduced the three-column theory, [14] which was followed later by Destot's two-row theory. [15] Multiple authors continued to refine and expand on this research introducing the ideas of “intercalated segment”, and “dorsal intercalated instability and volar intercalated instability”, recognizing the difference and importance of stability in the proximal and distal carpal rows. [16, 17] However, with each new theory describing wrist motion, the complexity of accurately describing the wrist joint continues to evolve. Recently, a unifying theory of wrist motion based upon functional use of the wrist has been proposed. [5] Our findings would tend to support this theory, as it appears that both the RC and MC joints have evolved to have similar ROM and a similar path of motion.

Multiple authors have illustrated the importance of describing functional wrist motion in combined, coupled oblique planes of motion. [1, 18, 19] Given the importance of this arc of motion in daily function and especially in ballistic tasks such as throwing and clubbing or hammering, it would intuitively make sense that this motion be preserved across both joints; if the principal axes were not aligned, ballistic tasks would likely generate large stresses between joints whose principal direction of motion were not aligned with the surrounding joints or the direction of motion. However, to our knowledge, this biomechanical hypothesis has not previously been investigated. DTM has even been reported as a uniquely human trait, providing a survival advantage throughout the evolution of *Homo sapiens*. [2, 20] If

this is indeed true and the wrist has evolved to best function with a DTM, our findings are understandable.

This study has limitations. Given our study design, we were unable to distinguish the individual contributions of each joint to ROM and the mechanical properties of the wrist. As wrist motion was defined by movement of the metacarpals with respect to the forearm, motion was gauged as an aggregate of wrist (intact group), RC (sPCF group) and MC motion (sRCF group). Therefore, our results can only be interpreted as a summation of motion across the joints and consequently, our findings are limited in identifying which joint articulations are specifically responsible for these observed mechanical properties. Furthermore, because motion at the RC and MC joints was determined with sPCF and sRCF, respectively, it is possible that the resulting motion arc at the RC and MC joints was a product of the adjacent fusion, rather than the inherent motion arcs of these joints in an unfused wrist. Another limitation is the method of using pins to simulate fusion, which could allow for micromotion at the simulated fusion interfaces. To address this issue, we used 1.5 Nm moments (compared to 2.0 Nm in our previous study) [11], and monitored for bending of the pins during the study. Nevertheless, the possibility remains that there was motion that occurred at locations other than the joints that were studied. Further investigation is warranted to help distinguish more precisely the exact contributions of the various anatomic structures. We recognize that caution must be used when interpreting these results as it is impossible to predict in vivo properties from the use of cadaver tissue. Finally, as we chose to only test the wrists with the forearms transected, it remains unclear if these results would be observed with differing degrees of elbow flexion, extension and pronosupination.

Despite these limitations, our results provide a further understanding of wrist function and may provide additional information of the functional limitations with wrist injury and surgery. Additionally, as therapists continue to design therapeutic programs to restore maximal functional use of the wrist, the findings from our study would tend to support programs that prioritize recovery of DTM in postoperative rehabilitation following both MC and RC arthrodeses. Furthermore, this data provides valuable information to consider in multiple surgical procedures, including partial fusions and wrist arthroplasty, and suggests that either midcarpal or radiocarpal fusion may allow for the native direction of wrist motion to be resumed postoperatively.

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Clinical Relevance

These findings suggest that the RC and MC joints can each contribute to a similar mechanical axis of motion located along the path of DTM when the other joint has been eliminated via fusion. Surgical options such as partial wrist fusions may maintain the native wrist's mechanical axis if either the RC or MC joint is preserved, despite significant reduction in overall ROM.

Figure 1.

Specimen jig that interfaced to a standard materials testing system. The forearm, which was fixed in neutral rotation, was mounted to the jig horizontally. The application of 1.5 Nm moments in 24 different directions of wrist motion was achieved by rotating the specimen about the forearm axis and then locking the potting fixtures to the jig in 15° increments. Two orthogonal linear slides (depicted as x and y) allowed the specimen to travel freely in the horizontal plane, providing an unconstrained application of the moments and allowing the wrist to rotate about its physiological axes. Four constant 4.45 N force springs attached the flexors and extensors to the potting. (Reprinted from Crisco, JJ, Heard, WMR, Rich, RR, Paller, DJ, Wolfe, SW: The Mechanical Axes of the Wrist Are Oriented Obliquely to the Anatomical Axes. *J Bone Joint Surg Am* 2011;93:169–177 with permission from Wolters Kluwer Health, Inc.)

Figure 2.

Polar coordinate system to illustrate relationship between anatomic and mechanical axes relative to wrist position. This system is based on the assumption that wrist flexion-extension and radioulnar deviation axes are orthogonal to each other, with each direction comprising the four major directions of wrist motion. The remaining 20 directions, depicted as lines emanating from the center of the plot, are combinations of the two of the four major directions. The named directions (purple dotted lines) are equidistant (45°) from their two major direction components. For example, ulnar flexion is 45° from both pure flexion and ulnar deviation. The solid orange line depicts the plane of motion 15° from the ulnar flexion-radial extension axis, and 30° from the pure flexion-extension axis, that approximates the Dart-Throwers' Motion plane from our previous study.

Figure 3.
Steinmann pins placed in an oblique fashion across the carpal bones to simulate a pancarpal fusion (sPCF).

Figure 4.
Steinmann pins placed across the radiocarpal (RC) joint to simulate a radiocarpal fusion (sRCF).

Figure 5.

Bar graph a graph depicting comparison between intact, sRCF and sPCF groups with respect to each of the 6 major directions of motion: pure extension, ulnar deviation, 15° to ulnar flexion, pure flexion, radial deviation and 15° to radial extension. Note that the 15° to ulnar flexion-radial extension correspond to motion along the plane depicted by the orange line in Figure 2. A red asterisk (*) denotes significant difference between the intact group and the sRCF and sPCF groups. No significant differences were observed between the sRCF and sPCF groups for any of these directions. Error bars represent one standard deviation of the mean.

Figure 6.

Mean values for wrist motion for the intact, sRCF and sPCF groups are plotted relative to the directions of wrist motion to depict the overall motion envelope for each group. Note the substantial overlap of envelopes between the sRCF and sPCF groups. Colored arrows depict the mechanical axes of the intact (red), sPCF (blue), and sRCF (green) groups, oriented 26.6° , 22.2° and 20.4° from the anatomic flexion-extension axis, respectively (solid colored lines).