In Vivo Triquetrum-Hamate Kinematics Through a Simulated Hammering Task Wrist Motion

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Background: The shape and kinematics of the triquetrum-hamate joint have been the subject of continued research, as its articulation provides wrist stability and motion. The purpose of this study was to measure the in vivo articulation of the triquetrum-hamate joint as the wrist moves along an important functional wrist motion, the dart thrower's path.

Methods: The right wrist of six male and six female volunteers (average age [and standard deviation], 24.8 ± 3.8 years) were imaged with computed tomography in five positions along a simulated hammering task. Three-dimensional kinematics of the third metacarpal, triquetrum, hamate, and radius were analyzed with use of the rotation axis and the path of contact areas.

Results: As the wrist ulnar-flexed with respect to the radius, the triquetrum translated 3.7 ± 1.7 mm distally on the hamate. Approximately midway through this distal course, when the triquetrum appeared to engage the distal ridge of the hamate, the triquetrum began translating volarly. Total volar translation was 2.6 ± 1.1 mm. As the wrist ulnar-flexed, there was also a decrease in the distance and variability in the location of the triquetrum-hamate rotation axis from the hamate centroid: it decreased from 11.7 ± 4.1 mm to 3.3 ± 1.4 mm ($p < 0.0001$).

Conclusions: Our findings support the concept that the triquetrum rotates on the convex ellipsoid surface of the hamate and that the helicoidal description of the triquetrum's motion on the hamate may be an oversimplification.

Clinical Relevance: Our results suggest that the triquetrum-hamate joint is less constrained in radial extension than it is in ulnar flexion. The concave distal ridge of the hamate may guide the triquetrum toward the hook of the hamate until it is fully engaged, which could block further ulnar deviation of the wrist. This may provide carpal stability while also serving as a rationale for triquetrum excision to increase the range of motion of the wrist.

The ulnar-sided triquetrum-hamate joint has received less attention than its radial counterparts, although its unique articulation plays a vital role in carpal stability¹. For normal carpal stability, there is a balance between the flexion moment of the scaphotrapezotrapezoid joint and the extension moment of the triquetrum-hamate joint. These moments have been described as a spring with two distally directed arms, where any alteration in the moment arm of the triquetrum-hamate joint disrupts the equilibrium and results in non-dissociative volar intercalated segmental instability^{2,3}. Although the role of the triquetrum-hamate joint in carpal stability has been well accepted, the exact kinematics and

kinetics by which the triquetrum-hamate joint imparts an extension moment on the lunate are unknown. While the triquetrum-hamate joint has been shown to allow for static wrist stability in a grip, its role in dynamic stability and wrist motion has received less attention. Clinically, however, Bain et al. showed that triquetrum excision leads to 15° to 27° of increased ulnar deviation of the wrist in the setting of radio-scapholunate fusion and distal scaphoidectomy for radiocarpal arthritis⁴. This finding agreed with those in prior cadaveric studies that showed that triquetrum excision led to increased ulnar deviation of the wrist after radioscapulohumate fusion with distal scaphoidectomy or four-corner fusion with distal

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scaphoidectomy^{5,6}. To our knowledge, there has been no biomechanical evaluation of the role of the triquetrum-hamate joint in the wrist range of motion or any explanation for the increase in ulnar deviation achieved by triquetrum excision.

The purpose of this study was to measure the in vivo articulation of the triquetrum-hamate joint as the wrist moves along the dart thrower's path. We chose the dart thrower's path because it provides a stable base for common grip activities and has been suggested as being the most important functional motion of the wrist^{7,8}. Furthermore, to our knowledge, the articulation of the triquetrum-hamate joint has yet to be studied as the wrist moves through the dart thrower's path. We studied triquetrum-hamate motion using an accurate markerless bone registration technique applied to serial computed tomography (CT) scans of the wrist as it moved along a simulated hammering task.

Materials and Methods

Data Collection

Following institutional review board approval and provision of informed consent, six male and six female right-handed volunteers with an average age (and standard deviation) of 24.8 ± 3.8 years were screened by a board-certified orthopaedic hand surgeon (E.A.) with radiographs and physical examination to confirm the lack of any injury or diseases that would affect carpal motion. Subjects held a dowel (a simulated hammer handle) and placed the right wrist in a custom jig designed to hold the wrist steady at five evenly-spaced wrist positions along a simulated hammering task⁹. CT scans (GE LightSpeed 16; GE Healthcare, Milwaukee, Wisconsin) of the wrist were obtained beginning in radial extension and moving toward ulnar flexion through each of five hammering positions: -40° (maximum radial extension, the beginning of the hammering task), -20° , 0° (neutral, with the hammer handle perpendicular to forearm), 20° , and 40° (the end of the hammering task). Imaging parameters were set at 80 kVp and 80 mA, with 0.5×0.5 -mm in-plane resolution and a slice thickness of 0.625 mm. To provide better-quality three-dimensional bone surface models and aid the registration algorithm, a sixth, higher-resolution neutral scan ($0.3 \times 0.3 \times 0.625$ mm) was also acquired. Only one trial was completed by each subject to minimize radiation exposure, as a prior study showed only a small hysteresis effect in the wrist¹⁰.

Data Analysis

An established markerless bone registration method^{11,12} was used to calculate relative motion between each sequential hammering position for the third metacarpal, the hamate, and the triquetrum with respect to the radius as well as the triquetrum with respect to the hamate. This resulted in four hammering steps (-40° to -20° [motion H1], -20° to 0° [motion H2], 0° to 20° [motion H3], and 20° to 40° [motion H4]). Each step was described with use of the helical axis of motion variables that completely describe three-dimensional motion about a single rotation and translation along a unique axis, referred to as the rotation axis. The orientation of the rotation axes of each bone with respect to the radius was reported as a function of the hammering position, in a radius-based coordinate system¹³. The components of the triquetrum-hamate rotations (the triquetrum with respect to the hamate) in each anatomical direction were reported as the percent of the total rotation about the axes of a coordinate system that was aligned with hamate anatomy. The x-axis was directed from the proximal pole of the hamate toward the distal end. The y-axis was directed from dorsal to volar such that it was parallel with the hook of the hamate, and the z-axis was directed from the ulnar to the radial aspect of the hamate. The variability in rotation axis orientation across subjects was reported as the mean angle between each subject's rotation axis and the average of all subjects' rotation axes. The location of the triquetrum-hamate rotation axis throughout the path was reported as the distance of the closest approach of the

rotation axis to the centroid of the hamate. Differences between the rotation axes of the triquetrum and hamate during the hammering motion were evaluated with use of a two-way repeated-measures analysis of variance (ANOVA) and a Holm-Sidak comparison procedure.

The translation of the triquetrum on the hamate was also described by the path of the centroid of the contact area of the triquetrum-hamate joint. Because the cartilage was not imaged directly, the contact area was estimated with use of the distances between the subchondral bone of the triquetrum and hamate. Iso-contour distances were calculated according to previous methods¹⁴, and the region on the subchondral bone surface of the hamate that was within 1.8 mm of the triquetrum was determined. A value of 1.8 mm was chosen on the basis of an estimated thickness of the articular cartilage on each facet of approximately 0.9 mm. The centroid of the 1.8-mm contour region was then calculated for each of the five hammering positions. Centroid location in both the dorsal-volar and the proximal-distal direction of the hamate coordinate system was plotted as a function of the position along the hammering task. To determine if there was a relationship between centroid location and wrist position, linear regression analysis was performed at the subject level for each direction, and significance was tested to determine if the slope was non-zero with use of an F test. Correlation coefficients (R^2) were also calculated to examine the fidelity of the linear model.

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Results

Kinematics of the Wrist (Third Metacarpal), Triquetrum, and Hamate with Respect to the Radius

Throughout the hammering task, the wrist ulnar-flexed through a mean range of motion (and standard deviation) of $71.1^\circ \pm 8.1^\circ$ (Fig. 1, Table I). The coupling ratio of flexion-extension to ulnar-radial deviation was linear ($p < 0.01$), with a mean value of $1.14^\circ \pm 0.43^\circ$. This is equivalent to 1.14° of flexion-extension for every 1° of ulnar-radial deviation. The motion was biased toward wrist extension, with the amount of extension changing from $59^\circ \pm 9.6^\circ$ during the beginning of the hammering motion (-40° hammering position) to $8^\circ \pm 10^\circ$ at the end of the hammering task (40° hammering position). The orientation of the rotation axis of the wrist was approximately midway between the flexion axis and the ulnar deviation axis as the wrist moved through the first four hammering positions (-40° to 20°). As the wrist moved from the fourth (20°) hammering position to the last (40°) hammering position, it primarily flexed, as shown by a significant shift ($p < 0.001$) in the angle that the rotation axis made with the flexion axis from $43.8^\circ \pm 15.6^\circ$ at -40° to $27.2^\circ \pm 10.3^\circ$ at 40° (Fig. 1, H4). The hamate rotated about a rotation axis that was oriented nearly parallel to the third metacarpal axis ($p = 0.7$), but it rotated by approximately 2.0° less during each progressive hammering step ($p < 0.001$). There were no significant differences in the orientation of the triquetrum rotation axis with respect to either the third metacarpal or the hamate rotation axis, although the orientation of the triquetrum rotation axis was less consistent than that of the third metacarpal and hamate rotation axes throughout the hammering motion. This was shown by larger variability in the triquetrum rotation axis orientation (19.8° compared with 9.0° and 10.5° for the third metacarpal

TABLE I Rotation and Orientation of the Third Metacarpal, Hamate, and Triquetrum with Respect to the Radius Throughout the Hammering Motion

Motion	Mean (Stand. Dev.) (deg)					
	Wrist (Third Metacarpal)*		Hamate*		Triquetrum*	
	Rotation	Orientation	Rotation	Orientation	Rotation	Orientation
Total motion (H1-H4)	71.1 (8.1)	41.0 (9.0)	62.0 (6.7)	47.1 (10.5)	27.5 (5.9)	76.1 (19.8)
Motion H1 (−40° to −20°)	17.6 (4.0)	46.3 (18.0)	14.2 (4.7)	55.4 (23.1)	7.8 (3.0)	51.9 (25.6)
Motion H2 (−20° to 0°)	19.4 (2.3)	49.5 (17.7)	17.7 (2.2)	57.2 (19.4)	8.4 (2.9)	88.1 (35.8)
Motion H3 (0° to 20°)	20.3 (4.9)	43.8 (15.6)	18.5 (4.4)	49.6 (17.4)	8.9 (2.5)	101.0 (29.1)
Motion H4 (20° to 40°)	16.9 (4.5)	27.2 (10.3)	15.9 (4.5)	28.5 (10.7)	7.7 (3.0)	63.4 (25.0)

*Rotation is described about the rotation axis. Orientation is the angle formed between the rotation axis and the wrist flexion axis, where 0° = pure flexion, 90° = ulnar deviation, 45° = ulnar deviation and flexion, and 180° = pure extension.

and hamate rotation axes, respectively). The triquetrum rotated approximately 10° less ($p < 0.001$) than either the third metacarpal or the hamate at each hammering step, which resulted in a range of motion that was $44\% \pm 11\%$ of the range of motion of the hamate. Although there were no significant differences in the orientations of the triquetrum rotation axes (likely due to the increased variability), the triquetrum ulnar

deviated more than it flexed and, in some cases, extended while ulnar deviating during the middle hammering steps (the 20° to 0° and 0° to 20° hammering steps) (Fig. 1, H3).

Rotation of the Triquetrum with Respect to the Hamate

Qualitatively, we observed that, as the wrist moved into ulnar flexion, the triquetrum translated along the hamate distally and

Fig. 1
Motion of the third metacarpal (MC3), hamate (HMT), and triquetrum (TRQ) with respect to the radius (RAD) as seen on a volar view of a right wrist. The radius-based coordinate system is imbedded in the radius with the flexion-extension axis (F/E) shown in green and the ulnar-radial deviation axis (U/R) shown in blue. The gray bone represents the first position and the colored bone represents the second position, as the wrist is moved from the −40° to the −20° hammering position (motion H1), from the −20° to the 0° hammering position (motion H2), from the 0° to the 20° hammering position (motion H3), and from the 20° to the 40° hammering position (motion H4). The color of the rotation axis of each bone coincides with the bone color. The third metacarpal and hamate rotate similarly, while the triquetrum has a range of motion that is less than half that of the third metacarpal and hamate.

TABLE II Total Rotation of the Triquetrum Relative to the Hamate and Its Components with Respect to Hamate Anatomy

Motion	Total Rotation (deg)	Mean (Stand. Dev.)			
		Radial (+)/ Ulnar (–) (%)	Volar (+)/ Dorsal (–) (%)	Distal (+)/ Proximal (–) (%)	Rotation Axis Variability* (deg)
Motion H1 (–40° to –20°)	7.9 (3.4)	12 (25)	–35 (25)	40 (23)	33.7
Motion H2 (–20° to 0°)	12.2 (3.6)	–18 (15)	–35 (11)	42 (12)	16.0
Motion H3 (0° to 20°)	14.6 (5.3)	–30 (12)	–33 (10)	36 (9)	14.6
Motion H4 (20° to 40°)	10.8 (5.6)	–45 (11)	–24 (14)	28 (9)	15.2

*Rotation axis variability is calculated as the average angle between each subject's individual rotation axis and the average rotation axis of all subjects.

volarly in a path oblique to the sagittal plane along the ulnar surface of the hamate (Fig. 2). As the triquetrum approached the distal aspect of the ulnar surface (at a prominent ridge), it shifted from an oblique course to a volar course, toward the convex surface of the base of the hook. This shift in motion corresponded to a change in the location of the rotation axis from outside of the hamate in a variable orientation, to within the hamate in a predominantly radial-ulnar orientation (rotation axis variability, 15.2°) (Table II, Fig. 2). The closest distance and variability in the location of the triquetrum-hamate rotation axis from the hamate centroid decreased from 11.7 ± 4.1 mm to 3.3 ± 1.4 mm ($p < 0.0001$), from the first

hammering step (–40° to –20°, H1) to the last hammering step (20° to 40°, H4). The variability in orientation of the rotation axis also decreased from the first step to the last step. This was expressed as the angle between the average rotation axis (across subjects) and each subject's rotation axis decreasing from 33.7° to 15.2°.

Translation of the Triquetrum on the Hamate

The path of the centroid of the contact area mirrored triquetrum motion and confirmed our visual findings (Fig. 3, a and b). There was a positive linear ($R^2 = 0.93 \pm 0.06$) relationship ($p < 0.05$) between the proximal/distal movement of the

Fig. 2

Oblique (volar-ulnar) view of a right wrist. The rotation axis of the triquetrum (TRQ) with respect to the hamate (HMT) moves from a variable location outside the hamate to a radial-ulnar orientation within the hamate as the wrist moves through the hammering task. The gray triquetrum represents the first position and the colored triquetrum represents the second position as the wrist moved from the –40° to the –20° hammering position (motion H1), from the –20° to the 0° hammering position (motion H2), from the 0° to the 20° hammering position (motion H3), and from the 20° to the 40° hammering position (motion H4). CAP = capitate.

Fig. 3

a: Translation of the triquetrum on the hamate. The position of the triquetrum (colored) on the hamate (gray) at the -40° hammering position (red), at the 0° hammering position (green), and at the 40° hammering position (blue). b: The 1.8-mm contour centroid and corresponding area for the same positions in a. The black spheres represent the intermediate hammering positions. c: Proximal-distal contour-centroid location versus dart thrower's path for each subject and a linear function fit to each subject. d: Dorsal-volar contour-centroid location versus dart thrower's path and a quadratic function fit to each subject.

contour centroid and the hammering task (Fig. 3, c). The total excursion of the contour centroid along the proximal-distal path was 3.7 ± 1.7 mm. As the triquetrum moved distally, it began moving in a volar direction toward the base of the hook of the hamate (Fig. 3, d). In this plane, the triquetrum translated 2.6 ± 1.1 mm and had a positive linear relationship with the dart thrower's path in eight of the twelve subjects ($p < 0.05$). Interestingly, dorsal-volar movement of the contour centroid location along the hammering task was better modeled by a quadratic function, with R^2 values increasing from 0.74 ± 0.22 in a linear model to 0.96 ± 0.03 in a quadratic model.

Discussion

This study describes the in vivo kinematics of the triquetrum-hamate joint during combined motions of ulnar-radial deviation and flexion-extension, specifically motion along a dart thrower's path. The shape and articulation of the triquetrum-hamate joint has been the subject of some controversy. It was originally described as a saddle-shaped joint because the surfaces of the hamate and triquetrum have both concave and convex parts¹⁵. Additional studies extended the saddle joint concept to describe the concave and convex parts of the hamate as forming a spiral groove that causes a helicoidal or screw-type motion of the triquetrum as it articulates with

the hamate^{16,17}. Recently, Moritomo et al. measured the in vivo kinematics of the triquetrum-hamate joint throughout the orthogonal motions of ulnar-radial deviation and flexion-extension and found that the triquetrum articulates primarily with the convex surface of the hamate, making the joint ellipsoidal rather than saddle-shaped or helicoidal¹⁸. We found that, as the triquetrum moved distally on the hamate, there was little dorsal-volar translation early in radial extension, with volar translation increasing as the wrist moved into ulnar flexion. These findings suggest that the helicoidal description of the triquetrum's motion on the hamate is an oversimplification¹⁶. True helicoidal or screw motion implies a constant ratio of proximal-distal translation to dorsal-volar translation of the triquetrum as it spirals along the hamate groove. Instead, our findings suggest that the motion of the triquetrum is more complex, as the amount of dorsal-volar translation increases with increasing distal translation. Our findings support the concept that the motion of the triquetrum can be explained by rotation on the convex ellipsoidal surface of the hamate as suggested by Moritomo et al. Our results suggest that the concave distal ridge of the hamate may guide the triquetrum as it articulates with the convex part of the hamate, until its translation ends at the hook of the hamate. The triquetrum first rotates about a minor axis (a larger radius of curvature) of the ellipsoidal surface of the hamate, and finally rotates about the long axis (a smaller radius of curvature) of the ellipse, as evidenced by the rotation axis moving from outside the body of the hamate to within the hamate in a radial-ulnar orientation.

Carpal kinematics depend on the geometry of each carpal bone¹⁹ and the constraints of the extrinsic and intrinsic carpal ligaments¹. Carpal stability under load is maintained by a balance between the flexion moment of the scaphoid and the scaphotrapezotrapezoid joint, and the extension moment of the triquetrum-hamate joint^{1,2}. The scaphoid, by virtue of its obliquity, tends to rotate into flexion during radial deviation, creating a flexion moment on the lunate^{1,2}. Conversely, the flexion moment of the scaphoid is balanced by an extension moment from the triquetrum-hamate joint during ulnar deviation. The current understanding of the function of the triquetrum-hamate joint is based on its roughly helicoidal shape creating an extension moment on the triquetrum, with an additional extension moment on the triquetrum from the flexor carpi ulnaris tendon during ulnar deviation, although this continues to be studied²⁰. The dynamic relationship between these two balancing moments is highlighted by the creation of a volar intercalated segmental instability deformity of the carpus after a lunotriquetral ligament disruption, and a distal intercalated segmental instability deformity of the carpus after a scapholunate ligament disruption or after scaphotrapezotrapezoid degeneration². Because our study is limited to a kinematic analysis, without regard to the forces or moments that cause the motions, we cannot make definitive statements on the role of the triquetrum-hamate articulation in joint stability. However, the decrease in variability in both the location and the orientation of the rotation axis of the

triquetrum-hamate joint as the wrist moves along the dart thrower's path implies that the joint is less constrained in radial extension than it is in ulnar flexion.

The lack of constraint in radial extension may imply that the joint has more mechanical play in this position or it may be due to variations in the shape of the bone surfaces among subjects. We are unsure if an extension moment is created in the triquetrum-hamate joint as the wrist goes into ulnar deviation through the dart thrower's path, or if stability is imparted simply by the articulation of the triquetrum with the distal ridge and base of the hook of the hamate. Future studies are needed to better understand the kinetic role of the triquetrum-hamate joint and its osseous articulation and ligamentous constraints. Because prior studies have shown variations in kinematics between wrists with Type-1 and Type-2 lunates, we analyzed our data to determine the lunate types on radiographs. Type-1 (n = 3), Type-2 (n = 7), and intermediate (n = 2) lunates were identified by radiography, but we were unable to detect differences in kinematic patterns among these groups²¹. This is likely due to the small sample size, but given the consistent patterns across subjects, we would expect only small differences in triquetrum-hamate kinematics among different lunate types.

Recently, Pervaiz et al. and Scobercea et al. described triquetrum excision leading to increased flexion-extension and radial-ulnar deviation of the wrist after radioscapholunate fusion⁵ and midcarpal arthrodesis⁶. While triquetrum excision has shown clinical success in terms of allowing increased wrist motion, no biomechanical study has explained why this procedure is effective, to our knowledge. Our study suggests that the distal ridge of the hamate may guide the triquetrum toward the hook of the hamate until it is fully engaged and fully constrained at the end of the dart thrower's path (flexion and ulnar deviation). This constrained position of the triquetrum at the hook of the hamate may serve as a stop, to prevent further wrist ulnar deviation. On the basis of this understanding, surgical procedures that excise the triquetrum would allow for increased ulnar deviation. From a kinetic standpoint, excising the triquetrum would lead to a volar intercalated segmental instability deformity of the wrist due to loss of the extension moment of the triquetrum-hamate joint on the lunate. In the setting of midcarpal or radiocarpal fusions, however, the carpus can be stabilized in neutral, while triquetrum excision would allow for increased wrist motion.

Our study had several limitations. First, kinematic data were generated from CT images in five static positions along the hammering task. While a prior study has shown that there is a hysteresis effect with dynamic motions, it was demonstrated to be small and should not have had an effect on our analysis¹⁰. Second, subjects passively held a dowel rod during CT scanning and were not actively swinging, as would be done in true hammering. We do not believe that the kinematics of the carpus is significantly affected by the lack of active swinging or that this factor limits our conclusions.

To our knowledge, this is the first description of in vivo triquetrum-hamate kinematics through a dart thrower's

motion based on a three-dimensional markerless bone registration technique. A complete understanding of the kinetics and kinematics of the triquetrum-hamate joint is important for understanding wrist stability through various ranges of motion, including the dart thrower's path, and may aid in the treatment of wrist disorders, including clunking wrists and dissociative carpal instabilities. Our results provide a more complete understanding of triquetrum-hamate joint kinematics through the dart thrower's path, and also provide a biomechanical basis for future research into carpal stability and triquetrum excision with limited wrist fusion for carpal instabilities. ■

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