Abstract

The capitate is often considered the “keystone” of the carpus, not simply because of its central and prominent position in the wrist, but also because of its mechanical interactions with neighboring bones. The purpose of this study was to determine in vivo three-dimensional capitate kinematics. Twenty uninjured wrists were investigated using a recently developed, non-invasive markerless bone registration (MBR) technique. Surface contours of the capitate, third metacarpal and radius were extracted from computed tomography images of seven wrist positions and the three-dimensional motions of the capitate and third metacarpal were calculated with respect to the radius in wrist flexion–extension and radio-ulnar deviation. We found that in vivo capitate motion does not simply occur about a single pivot point like a universal joint, as demonstrated by non-intersecting rotation axes for different capitate motions. The distance between flexion and ulnar deviation axes was $3.9 \pm 2.0$ mm, and the distance between extension and ulnar deviation axes was $3.9 \pm 1.4$ mm. Furthermore, capitate axes for males tended to be located more distally than axes for females. However, we believe that this result is related to subject size and not to gender. We also found that there is minimal relative motion between the capitate and third metacarpal during these in vivo wrist motions. These findings demonstrate the complexity of capitate kinematics, as well as the different mechanisms through which wrist flexion, extension, radial deviation and ulnar deviation occur.

Keywords: In vivo; Wrist; Capitate; Carpal kinematics; Three-dimensional

1. Introduction

The capitate is anatomically situated in the distal carpal row of the wrist and can be considered the functional “keystone” of the carpal bones. Distally, the capitate articulates closely with the third metacarpal and has subsequently been used as an indicator of wrist motion in flexion and extension (e.g. Patterson et al., 1998). Proximally, the capitate articulates with the lunate and scaphoid, two bones that are clinically essential to normal wrist function (e.g. Garcia-Elias et al., 1989). Additional studies of wrist motion have provided information regarding the functional and mechanical significance of the capitate (e.g. de Lange et al., 1985; Ruby et al., 1988; Savelberg et al., 1993).

Previous studies have reported variations in the location of the center of wrist motion. One in vitro (cadaveric) study reported that the motion of the wrist is centered about a single pivot point located in the capitate (Savelberg et al., 1993). This implies that the wrist functions as a universal joint, such that all motion axes pass through a single point located in the proximal pole of the capitate. Several in vivo studies suggested that wrist motion occurred about orthogonal and non-intersecting axes in the proximal capitate (e.g. Andrews and Youm, 1979, Brumbaugh et al., 1982), which implies that flexion–extension motion axes are perpendicular to radio-ulnar deviation motion axes. A separate in vitro study found that the center of wrist motion was not necessarily fixed within the proximal pole of the capitate during wrist flexion–extension (Patterson et al., 1998). Other in vivo studies suggest that flexion–
extension and radio-ulnar deviation motion axes may be skew to one another (e.g. Sommer and Miller, 1980).

These reported variations may be attributed to numerous factors. In vitro studies have largely used invasive techniques such as the implantation of radiopaque markers and rods which may have disrupted soft tissues or interfered with normal kinematics. In vitro studies are also inherently limited because if wrist loading with muscular forces is to be accounted for, they must be estimated and simulated. It has been proposed that small changes in wrist loading may have profound effects on wrist kinematics (Valero-Cuevas and Small, 1997). In vivo studies have examined only gross wrist motion not specific to the individual carpal bones. Additionally, some previous studies were based on two-dimensional kinematic analyses, and the importance of documenting three-dimensional kinematics has been noted (Wolfe et al., 1996).

Previous in vitro studies of wrist motion also found that the third metacarpal and capitate rotate together in wrist flexion–extension (e.g. Patterson et al., 1998). From these studies, the capitate has often been designated as an indicator of wrist motion. However, it is unclear if this finding can be extrapolated to in vivo capitate motions in other wrist directions (e.g. radio-ulnar deviation).

The purpose of the current study was to examine the in vivo three-dimensional kinematics of capitate motion with respect to the radius using markerless bone registration (MBR) (Crisco et al., 1999). This technique extends our functional understanding of the carpus as it is non-invasive, in vivo, and provides unique data of bone geometric properties (such as the three-dimensional volume, centroid, and surface shape) which aid in the description of kinematic parameters. Herein, we present a summary of the capitate rotations and translations observed using MBR. We question (1) if the capitate rotates about a single pivot point in its proximal pole or about different axes in wrist flexion, extension, radial deviation and ulnar deviation, and (2) if the capitate and third metacarpal rotate together in wrist flexion–extension and radio-ulnar deviation.

Each subject underwent simultaneous CT imaging of both wrists using a General Electric HiSpeed Advantage scanner (Milwaukee, WI). The subjects were positioned behind the scanner gantry in a specially designed chair. Wrist positioning in flexion–extension and radio-ulnar deviation was accomplished using protractor readings on a custom polycarbonate positioning jig (Fig. 1). Wrists were first scanned in a neutral position, which was defined by visually aligning the back of the hand with the back of the forearm and the third metacarpal with the long axis of the forearm. In addition to neutral, subject wrists were rotated to 30° and 60° of flexion, 30° and 60° of extension, 20° and 40° of ulnar deviation, and 20° of radial deviation, as determined by the protractor readings on the positioning jig. Continuous 1 mm image slices from the distal radius and ulna to the proximal heads of the metacarpals were acquired at each position (typically 60 image slices at 1 mm increments for each wrist position; pixel dimension ranged from 0.2 × 0.2 mm² to 0.9 × 0.9 mm²).

The contours of each bone were segmented from the CT volume images using Analyze™ software (Mayo Foundation, Rochester, MN), reconstructed using custom MATLAB software (Mathworks, Natick, MA), and then used to calculate bone physical properties and motions. Capitate volumes, centroid locations and principal axes orientations were determined from the bone contour data at each wrist position using equations developed previously (Crisco and McGovern, 1998). Prior to any calculations, all left wrist bone surfaces were mathematically reflected into right wrist bone surfaces to simplify subject comparisons. Reflection was accomplished by taking the negative of the X component of the bone surface coordinates and reversing the direction of the surface contours in each image slice.

The posture of the capitate in the neutral position was defined using the orientation of the first principal inertial axis of the capitate (defined as the principal axis about which the minimum bone inertia occurs and shown as I in Fig. 2) from the neutral bone contour data. In neutral, the orientation of the first principal axis (I) of the capitate was decomposed into two fixed angles relative to an anatomic coordinate system (described subsequently) and was found to be in extension and radial deviation (described in results). The extension posture was defined as the initial fixed angle between the first principal axis and the coronal (XY) plane of the anatomic coordinate system. Radial deviation posture was defined as the initial fixed angle between the XY projection of the first principal axis and the Z-axis. Additionally, the distance between respective neutral capitate centroids and anatomic coordinate system origins for each subject wrist was calculated.

Motion of the capitate and third metacarpal with respect to the radius was determined in a sequence of

2. Materials and methods

Both wrists of five male and five female uninjured subjects were studied using a computed tomography (CT) analysis with Institutional Review Board approval. Informed consent was obtained from all subjects prior to enrollment in the study. Subjects with a history of wrist trauma were not included in this study. The average age of the male and female subjects was 31.0 years (range 22–47) and 21.8 years (range 21–22), respectively.
steps. First, motion of the capitate, third metacarpal and radius for each wrist position was determined relative to the fixed CT-based coordinate system. Specifically, capitate rigid body motion transformations from the neutral wrist position to subsequent wrist positions were calculated by registering the respective principal axes of inertia and centroids of the capitate (Crisco and McGovern, 1998). This technique is valid only for bones whose surfaces were consistently or completely imaged in subsequent positions, since principal axes orientations and centroid locations vary with the amount of bone surface imaged bone surface. Because the scanned length of the third metacarpal and radius could not be consistently defined, registration in the fixed CT-based coordinate system was calculated for both of these bones by minimizing the root mean square distances between bone surfaces (Pelizzari et al., 1989).

Fig. 1. The wrist positioning jig is shown in the CT scanner. Subject hands were positioned in neutral, 30° and 60° of flexion, 30° and 60° of extension, 20° and 40° of ulnar deviation, and 20° of radial deviation using protractors affixed to the jig.

Fig. 2. Capitate principal axes of inertia are shown in a sagittal (A), proximal (B) and oblique (C) view of a typical neutral position, with respect to the anatomic coordinate system embedded in the distal radius. The first principal axis of inertia of the capitate is labeled I and was used to define neutral posture orientation.
Second, kinematic variables for the capitate and third metacarpal were described relative to an orthogonal distal radius-based anatomic coordinate system (Fig. 2). Anatomic features of the imaged radius were used to define the orientation of the coordinate system axes as the best fit of the diaphysis cross section centroids (+X is proximal), the intersection of the radial styloid peak orthogonal to X (+Y is radial) and the cross product of X and Y (+Z is palmar) (after Kobayashi et al., 1997).

The origin of the system was defined as the intersection of the X-axis and the distal radial surface.

Finally, capitate and third metacarpal motions from neutral to subsequent wrist positions were reported using the screw axis or helical axis of motion (HAM) variables, which are defined as a rotation about and a translation along a unique axis (e.g. Panjabi et al., 1981). The unique axis, defined by its orientation (direction cosines) and an arbitrary point along it, is referred to as a HAM axis. Additionally, the component of capitate rotations about X (supination-pronation), Y (flexion-extension) and Z (radio-ulnar deviation) anatomic axes were determined by multiplying the total rotation by the square of respective HAM axis orientation components.

Due to the large number of parameters required to completely describe the HAM axes for all subjects and all motions, HAM axes were pooled to answer specific questions and facilitate data descriptions. A motion axis was calculated by vector averaging the two HAM axes in each direction of wrist motion for each subject (subsequently referred to as a flexion axis, etc.). The orientation of the motion axis was calculated by normalizing the vector sum of the HAM axes. The location of the motion axis was defined by the midpoint of the mutually perpendicular line segment between the two HAM axes. Since only one HAM axis in radial deviation was generated for each wrist, the location of this motion axis was described by the point on the axis that was closest to the origin of the anatomical coordinate system. The orientation of the radial deviation motion axis for each subject was determined similarly to the other three motion axes. Finally, further calculations were made to describe motion axes parameters for groups of subjects (e.g. motion axis orientation for all subjects or just males, etc) by vector averaging the motion axes in a direction of wrist motion. Angular variation in the orientation of the motion axes from respective subject HAM axes was described by the average angle between these axes.

The existence of a single pivot point was examined using the distance between the closest points of each of the various motion axes (corresponding to the minimum distance and length of the mutually perpendicular line segment). Motion about a single pivot point, i.e. an “ideal” universal joint, required that the minimum distances between all motion axes be sufficiently small to be considered zero. The minimum distances for all possible pairs of motion axes were analyzed by comparing independently the xyz coordinates of the location of the closest points using a repeated measures one-way analysis of variance with Tukey-Kramer post-hoc tests (Instat, Graphpad Software, San Diego, CA). Additionally, the volume of male and female subject capitates were compared using an unpaired Student’s t-test.

The differences between capitate and third metacarpal motions were determined by comparing flexion-extension and radio-ulnar deviation rotations about HAM axes with a paired Student’s t-test. Additionally, the difference between protractor and capitate rotation measurements was compared using a paired Student’s t-test. Results are presented in terms of the mean±one standard deviation (SD).

3. Results

3.1. Capitate rotation and translation during wrist motion

Although a total of 160 CT scans were performed on our volunteers (20 subject wrists×8 CT scans per subject wrist = 160 CT scans), one of the resulting 160 CT volume images was discarded due to a motion artifact that occurred in the wrist of a subject during wrist flexion, leaving a total of 159 volume images for the full kinematic analysis.

In vivo capitate rotations and translations exhibited complex three-dimensional patterns during wrist motions (Table 1 and Figs. 3 and 4). The capitate rotated primarily about the flexion (+Y) axis during wrist flexion (Table 1) and ranged from approximately 7° to 70° (Fig. 3(A)). During wrist flexion, the capitate rotated 80±21% in flexion (+Y-axis), 14±12% in pronation (+X-axis) and 5±11% in ulnar deviation (+Z-axis), indicating that the largest non-flexion rotation occurred in pronation (Fig. 3(A)). Capitate translation along the HAM axis was less than 2.5 mm overall, and increased in an ulnar direction approximately 0.1 mm for every 10° of wrist motion (Fig. 4(A)).

The capitate rotated primarily about the extension (−Y) axis (Table 1) ranging from approximately −7° to −80° during wrist extension (Fig. 3(A)). The capitate rotated 89±7% in extension (−Y-axis), 2±2% in supination (−X-axis), and 9±8% in ulnar deviation (−Z-axis) (Fig. 3(A)). Capitate translation in a radial direction along the HAM axis increased approximately 0.4 mm for every 10° of wrist motion to less than 5 mm (Fig. 4(A)).

The capitate was found to rotate primarily about the extension (−Y) axis during radial deviation of the wrist (Table 1), which accounted for 75±25% of this wrist motion (Fig. 3(B)). The capitate rotated only 19±20% in radial deviation (−Z-axis), accounting for approxi-
Additionally, the capitate rotated 5.78% in pronation (+X-axis). Capitate translation along the HAM axis was less than 1.5 mm overall and increased in a radial direction approximately 0.1 mm for every 1° of wrist motion (Fig. 4(B)).

Capitate rotation occurred primarily about the ulnar deviation (+Z-axis) during wrist ulnar deviation (Table 1) and ranged from approximately 5° to 45° (Fig. 3(B)). The capitate rotated 90° ± 14% in ulnar deviation (+Z-axis), 2° ± 2% in pronation (+X-axis) and 8° ± 14% in extension (−Y-axis) (Fig. 3(B)). Capitate translation along the HAM axis increased approximately 0.8 mm for every 10° of wrist motion to less than 7 mm in a dorsal direction (Fig. 4(B)).

3.2. Capitate motion axes

In vivo capitate motion axes exhibited complex three-dimensional patterns during wrist motions (Tables 1–3 and Fig. 5). For each direction of wrist motion, variations between axis orientations and locations were considered sufficiently small to justify the use of a single motion axis for the results considered herein. The
angular variation of HAM axes from the motion axes was less than 12.0°, 9.7° and 17.7° for flexion, extension and ulnar deviation wrist motions, respectively (Table 1). The minimum distances between the two HAM axes in flexion, extension and ulnar deviation calculated were 0.8±0.8, 1.1±1.0 and 1.6±1.1 mm, respectively.

The capitate did not rotate about a single pivot point, as indicated by non-zero minimum distances found between various capitate motion axes (Table 2 and Fig. 5). A significant difference was found in the X component of the distance between flexion and ulnar deviation motion axes \((p < 0.001, \text{distance} = 3.9 \pm 2.0 \text{ mm})\). A significant difference was also found in the X component of the distance between extension and ulnar deviation motion axes \((p < 0.001, \text{distance} = 3.9 \pm 1.4 \text{ mm})\).

The location of the motion axes for the capitate was dependent on the direction of wrist motion and gender (Table 3). A comparison of the motion axis location \((X\text{ component})\) for all wrist motions suggested that the ulnar deviation motion axis was the most distal axis and the flexion and extension motion axes were the most proximal axes (Table 3). The standard deviation of the location of the motion axis was also greatest in the primary direction of the motion axis, as expected from the geometry of two acutely intersecting lines. Additionally, male axes tended to be located more distally than female axes.

Table 2

<table>
<thead>
<tr>
<th>Motion axes</th>
<th>Minimum distance between motion axes distance±SD (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexion and extension</td>
<td>1.9±1.6</td>
</tr>
<tr>
<td>Flexion and radial deviation</td>
<td>3.2±2.4</td>
</tr>
<tr>
<td>Flexion and ulnar deviation(^a)</td>
<td>3.9±2.0</td>
</tr>
<tr>
<td>Extension and radial deviation</td>
<td>2.7±2.8</td>
</tr>
<tr>
<td>Extension and ulnar deviation(^a)</td>
<td>3.9±1.4</td>
</tr>
<tr>
<td>Radial and ulnar deviation</td>
<td>3.7±2.4</td>
</tr>
</tbody>
</table>

\(^a\) \(p < 0.001\).

Table 3

<table>
<thead>
<tr>
<th>Motion</th>
<th>Gender</th>
<th>Motion axis location (X\±SD (mm), Y\±SD (mm), Z\±SD (mm))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexion</td>
<td>Male</td>
<td>(-12.7±3.1, -4.3±5.4, -0.6±1.4)</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>(-11.6±7.4, -3.4±19.5, 0.7±2.9)</td>
</tr>
<tr>
<td>Extension</td>
<td>Male</td>
<td>(-13.4±1.3, -2.8±5.3, -3.6±2.5)</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>(-8.9±2.5, 7.7±9.1, -5.4±2.2)</td>
</tr>
<tr>
<td>Radial deviation</td>
<td>Male</td>
<td>(-15.9±4.1, -0.2±4.6, -1.6±3.2)</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>(-11.4±2.1, -1.0±2.1, -1.7±2.2)</td>
</tr>
<tr>
<td>Ulnar deviation</td>
<td>Male</td>
<td>(-17.8±4.2, -6.9±4.8, -22.3±33.3)</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>(-15.3±2.0, -3.0±2.2, -13.6±28.6)</td>
</tr>
</tbody>
</table>

The capitate bone volumes of the male subjects were significantly greater \((p < 0.0001)\) than those of the female subjects, which is one possible explanation for more distally located male axes. The mean capitate volumes for our male and female subjects were 3231±542 mm\(^3\) (range: 2467–3998 mm\(^3\)) and 2220±205 mm\(^3\) range: 1987–2503 mm\(^3\)), respectively. Also, the distance of the capitate centroid to the origin of the anatomic coordinate system in the neutral position increased approximately linearly with the mean capitate volume (Fig. 6, \(r^2 = 0.65\)), demonstrating the association between distal axes
locations and capitate volume. Finally, the standard deviation of capitate volumes between scan positions was found to be less than 4.6% of the mean over all subjects, indicating that minimal segmentation error from the MBR technique influenced results.

3.3. Capitate as a measure of wrist position

The capitate and third metacarpal rotated together during wrist flexion–extension and radio-ulnar deviation. Over all positions in wrist flexion and extension, the mean difference in the rotation of the capitate and third metacarpal about respective HAM axes was $0.7 \pm 4.3^\circ$ and was not significantly different from zero ($p = 0.279$). In wrist radial and ulnar deviation, the mean difference in the rotation of the capitate and third metacarpal about respective HAM axes was $-0.3 \pm 4.4^\circ$ and was also not significantly different from zero ($p = 0.684$). Importantly, the capitate and third metacarpal rotated closely together despite the fact that pure in-plane motion for the capitate was not achieved (Fig. 3).

Differences were found between the positioning jig protractor readings and capitate measurements. Based on the orientation of the first principal inertial axis (shown in Fig. 7), the capitate’s neutral position was in $44.8 \pm 9.3^\circ$ of extension and $15.7 \pm 12.4^\circ$ of radial deviation. Also, the positioning jig protractor readings in flexion, extension, radial deviation and ulnar deviation did not agree with the calculated capitate rotations about HAM axes. The mean difference between protractor readings and capitate rotation measurements was found to be $9.0^\circ$ ($p<0.0001$). This discrepancy in protractor readings and rotation measurements was distributed over a range of wrist positions (note the scatter along the horizontal axis in Figs. 3 and 4).

4. Discussion

This study documented the in vivo three-dimensional motion of the capitate relative to the radius in the four primary directions of wrist motion. The motion axes analysis presented here suggests that the capitate does not rotate about a single pivot point and that wrist motions occur through complex carpal mechanisms. This conclusion is based on the finding that the flexion and extension axes locations both differed significantly from those of ulnar deviation. This finding demonstrates the complexity of capitate kinematics, the likely
resulting complex kinematics of neighboring bones (e.g. the scaphoid and lunate), and the different carpal mechanisms through which wrist motions occur.

Since complete data sets are unavailable, a comparison of our motion axes data to values found in the literature is difficult. A recent in vitro study of individual carpal kinematics reported a capitate pivot point located in the proximal capitate for a full range of wrist motions despite an average dispersion between HAM axes of 7.5 mm, although this study was limited by a small sample size ($n = 4$) (Savelberg et al., 1993). An early study of wrist kinematics found that the wrist acts as a simple hinge joint in both flexion–extension and radio-ulnar deviation wrist motions, with orthogonal axes separated by approximately 5 mm (Andrews and Youm, 1979). This study was limited, however, to the overall motion of the wrist, and was not designed to examine the individual motion of the capitate. Another study of overall wrist motion (Brumbaugh et al., 1982) found the flexion–extension and radio-ulnar deviation HAM axes passing through the proximal capitate for 15 subjects, although the distance of the common perpendicular between axes was as large as 6 mm in some individuals. The minimum distances calculated between motion axes in our in vivo study were less than these reported dispersions. A recent study qualitatively described instantaneous screw axes passing through the proximal capitate in wrist flexion–extension, although these axes were not all found to pass through the proximal pole of the capitate (Patterson et al., 1998). In contrast to that study, we found that flexion and extension motion axes passed through the proximal capitate, although they were separated by a distance of 1.9 mm. Finally, for the wrist motions we studied, our results support the finding of skew motion axes passing through the capitate (Sommer and Miller, 1980).

Our observation that axes in male subjects tended to be located more distal than those in female subjects can be attributed to the differences in subject anatomy. However, we were not able to exclude other possible reasons for the differences (e.g. subject age). Importantly, we were not able to detect differences in capitate rotation, translation, or motion axis orientation parameters between male and female subjects. However, because of significant differences in male and female bone volumes, we expected to see a difference in the location of the HAM axes relative to the distal radial surface. A relationship was found between the mean capitate volume and the neutral centroid location. If it is possible to accept the mean capitate volume and neutral centroid location as a measure of subject anatomical size, a relationship between the location about which capitate and wrist motion occurs and subject size may be suggested. This relationship, coupled with the inability to distinguish between other motion parameters, may suggest that rotation, translation and orientation of the wrist is not gender dependent and the location of the motion axis is simply related to carpal bone size. Interestingly, Savelberg et al. (1993) suggested that the location of the HAM axes of the capitate depends on the geometry of the specimen, although the relationship between geometry and size is unclear.

Since the capitate and third metacarpal rotated together during flexion–extension and radio-ulnar deviation motions, the use of the third metacarpal as an indicator of wrist motion (e.g. Patterson et al., 1998)
may also be extended to the capitate. Patterson et al. (1998) found an average difference of $1.1^\circ \pm 1.6^\circ$ in capitate-third metacarpal joint angles over wrist flexion and extension in a cadaveric study, and concluded that the joint was essentially rigid. Youm et al. (1978) also observed a maximum $2^\circ$ of relative motion between the capitate and third metacarpal and concluded that the two bones moved as a fixed unit. The results of our in vivo study are consistent with the findings of Patterson et al. and Youm et al.

Kinematic values for the capitate and third metacarpal were obtained using a non-invasive markerless bone registration (MBR) technique for carpal contours (Crisco et al., 1999). This methodology is robust to many different sources of error that can affect the accuracy of results. In a previous cadaveric study, we estimated the in vivo rotation error associated with bone registration to be less than $0.5^\circ$ for both the capitate and third metacarpal (Neu et al., 2000). The small calculated percent standard deviation of the capitate volume over the eight volume images for each subject indicates that minimal error was introduced due to segmentation and variations in CT image acquisition resolutions. Previously, Patterson et al. (1995) examined carpal bone anatomy with CT and segmented the carpal bones using an algorithm that automatically flexed a template over the image to optimally fit the bone contours (Tagare et al., 1993). Even though this segmentation approach was substantially different than ours, our capitate volume values agreed well with their values of $3434 \pm 1051$ and $2302 \pm 560$ mm for males and females, respectively (Patterson et al., 1995).

While the MBR technique implemented here allowed for the non-invasive description of in vivo capitate kinematics, limitations exist that must be considered when interpreting these results. It is important to note that only four directions of wrist motion were studied. It is unclear how the location and orientation of the HAM axes change when the wrist moves through combined motions, such as flexion and ulnar deviation, although it is reasonable to hypothesize that the axis will be some combination of these primary flexion and ulnar deviation axes. Variations in neutral capitate posture were evident, even though great care was taken to initially align the back of the hand with the back of the forearm. Additionally, we reported that appreciable out-of-plane capitate motions occurred during wrist motions and the orientation of radial deviation axes were most closely related to extension axes (Table 1). We believe that both these observations are due to the inherent difficulties associated with non-invasive in vivo studies. We also attributed the similarity of the radial deviation and extension axes to the prescribed wrist jig rotation. We later observed that subjects tended to pronate their forearms and extend their wrists when holding the grips of the wrist jig. However, the inability to precisely control capitate posture and motion was beneficial to examining the spectrum of capitate behavior. Further, it should be clear that in our analyses we used the actual rotation of the capitate to define wrist position and not the values of the wrist jig. Implications of these observations include the utility and validity of clinical protractor or goniometric measurements for carpal posture and motion. Also, the analysis of the data was limited to static positions, and it is unclear if the data may be applicable to describe dynamic motions of the wrist. Finally, our technique, in its present form, requires an extensive amount of computation time and user interaction.

The analysis outlined here provides an understanding of the capitate’s complex, three-dimensional kinematic behavior and function. An appreciation of capitate and third metacarpal rotations provides a more complete picture of the coupled relationship between these two bones. Also, an appreciation of the capitate’s kinematics provides a more comprehensive understanding of its effect on neighboring bones and the different mechanisms through which wrist motion occurs. Finally, the ability to visualize the kinematic data with respect to the bone surfaces provided by the non-invasive technique has aided in the understanding of the complex kinematic behavior observed herein.

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