Carpal Kinematics After Proximal Row Carpectomy

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Purpose: Proximal row carpectomy (PRC) is a clinically useful motion-sparing procedure for the treatment of certain degenerative conditions of the wrist. Clinical outcome studies after PRC have shown that wrist flexion–extension averages approximately 60% of that of the contralateral wrist. The purpose of this study was to determine how the kinematics of the wrist are altered after PRC.

Methods: Eight fresh-frozen cadaver forearms were scanned with computed tomography before and after PRC. Forearms were scanned in 5 different wrist positions (neutral, extension, flexion, radial deviations, and ulnar deviation). Wrists were positioned dynamically and then held statically in a custom fixture through forces applied to the 4 wrist flexor/extensor tendon groups. Three-dimensional computer models of the radius, lunate, and capitate were generated from the computed tomographic images, and the kinematics of the capitate and lunate were calculated relative to the neutral position. For the intact wrist, the motion of the capitate was calculated relative to both the lunate (midcarpal motion) and the radius (overall wrist motion) and the motion of the lunate was calculated relative to the radius (radiocarpal motion). After PRC, only the movement of the capitate relative to the radius was calculated, which represents radiocapitate and overall wrist motion. All motions were plotted in 3 dimensions for purposes of qualitative visualization.

Results: After PRC, the capitate articulated with the lunate fossa of the radius for all positions in all samples. Overall wrist motion decreased 28%, 30%, 40%, and 12% in flexion, extension, radial deviation, and ulnar deviation, respectively. Motion at the radiocarpal joint after PRC, however, was greater compared with motion at the radiocarpal and midcarpal joints of the intact wrist during flexion and extension. This was not the case in radial deviation because of impingement of the trapezoid on the radial styloid. In radial and ulnar deviation, motion of the capitate head changed from predominantly rotational in the intact wrist (midcarpal joint) to a combination of rotation and translation after PRC (radiocarpal joint).

Conclusions: Removal of the proximal carpal row decreased normal wrist flexion and extension. Although ulnar deviation was preserved, radial deviation was limited by impingement of the trapezoid on the radial styloid. Radiocapitate range of motion after PRC was greater than capitolunate range of motion in the intact wrists. Compared with previously published requirements, wrist range of motion observed after PRC was sufficient for activities of daily living. (J Hand Surg 2007;32A:37–46. Copyright © 2007 by the American Society for Surgery of the Hand.)

Key words: Carpal kinematics, proximal row carpectomy.

Previous clinical studies have shown that proximal row carpectomy (PRC) is a clinically useful motion-sparing procedure for the treatment of degenerative conditions of the proximal carpal row such as scapholunate advanced collapse, scaphoid nonunion advanced collapse, chronic perilunate dislocation, and Kienböck’s disease. Compared with limited wrist arthrodesis, PRC is technically easier, has fewer complications, and provides similar pain relief and grip strength.
Clinical studies\(^1,3\)--\(^5,8,11\) have shown that range of motion (ROM) after PRC and limited wrist arthrodesis is decreased compared with the contralateral side, with PRC resulting in greater loss of radial deviation compared with limited wrist arthrodesis. Cohen and Kozin\(^1\) reported that 62% and 51% of flexion–extension and radioulnar deviation ROMs, respectively, were obtained after PRC compared with the contralateral side. DiDonna et al\(^3\) showed that patients maintained 62%, 60%, 47%, and 73% of flexion, extension, radial deviation, and ulnar deviation, respectively, after PRC compared with the contralateral side. These studies have noted the greatest loss of motion to be in radial deviation, which is attributed to radiocarpal impingement.

Despite the reported clinical use of PRC for many decades, few studies have looked at biomechanics after PRC. Hogan et al\(^14\) recently published a study of the radiocarpal loading characteristics after PRC. This study showed that there was increased contact area and increased average pressure within the lunate fossa after PRC. In addition, there was greater excursion of the contact point within the lunate fossa.

Carpal kinematics have been most commonly represented with either helical axis of motion analyses or Euler angles. Helical axis of motion analysis allows characterization of 3-dimensional (3D) rigid body motion as a rotation about and a translation along an instantaneous axis of rotation in space.\(^15\)--\(^20\) Euler angles permit the characterization of wrist motion as component rotations about the anatomic axes of flexion–extension, radioulnar deviation, and pronosupination.\(^21\)--\(^26\)

The use of computed tomography (CT) to more precisely measure carpal kinematics has been used by previous investigators.\(^27\) This technique is noninvasive and can be used in vivo. Crisco et al\(^28\)--\(^30\) and others\(^24,31\)--\(^35\) have reported on the use of CT models to quantify carpal kinematics with both helical axis and Euler angle representations of motion.

We have developed a cadaveric model to quantify carpal kinematics during wrist flexion–extension and radioulnar deviation with CT. This model provides accurate carpal kinematics and results similar to those seen in vivo.\(^36\) The objective of this study was to use our model to characterize the effect of PRC on carpal kinematics.

**Materials and Methods**

Eight fresh-frozen cadaveric forearms (4 female, 4 male; age range, 18–45 y) were used in this study. Forearms were subjected to our previously described and validated methodology for measurement of carpal kinematics with CT.\(^36\) Each forearm was thawed, and all soft tissues overlying the middle third of the radius and ulna were removed except for the interosseous membrane and the wrist flexor/extensor tendons. A running stitch (no. 2 polyester braided suture) was placed into the proximal free end of each wrist flexor/extensor tendon. The extensor carpi radialis longus and extensor carpi radialis brevis sutures were tied together for simplicity. Each forearm was secured to a testing fixture in neutral forearm rotation with bolts passed through two 2.5-mm holes that were drilled through the midshaft of both the radius and ulna (Fig. 1). The wrist tendon sutures were then attached to spring scales on the testing fixture. An acrylic registration block was glued to the dorsal surface of the distal radius for use as a common reference frame in different wrist positions, as described in prior studies.\(^37\)

By manually varying the force applied to each tendon through the spring scales, the wrists were moved dynamically. When a desired position was achieved, this position was held statically by clamping cables attached to the proximal end of the spring scales to the test fixture. We applied forces ranging between 5 and 50 N to each tendon as needed to position the wrists, in a similar fashion as described by Werner et al.\(^38\) These forces were within a physiologic range for wrist tendon loading.\(^39\) Computed tomography images were obtained with the wrists held statically in positions of neutral and maximal flexion, extension, radial deviation, and ulnar deviation. Helical

![Figure 1. Testing fixture used to hold the forearm in the CT scanner. Wrist were positioned dynamically by varying the forces applied to the wrist tendons and held statically in each position by clamping the spring scales to the base of the test fixture.](image-url)
CT scans (140 kV, 80 mA, 10-cm field of view, 512 × 512 matrix with bone algorithm reconstruction) were obtained in each position with 1 mm between images. After scanning in all positions, a PRC was performed in each wrist by excising the scaphoid, lunate, and triquetrum through a dorsal longitudinal incision. Radial styloidectomy was not performed. The joint capsule and skin were reapproximated with 2-0 polyester braided suture, and the wrists had CT scanning in the same manner as the intact wrists.

Computed tomography images were processed and kinematics calculated with our previously described methodology. For each dataset, 3D computer reconstruction models of the capitate, lunate, and radius were created for the intact wrists and for capitate and radius after PRC. The center of mass and principal moments of inertia were generated for each model, and the kinematics of the capitate and lunate were determined for the motions from neutral to each position using both helical axis of motion and Euler angle representations. We have shown that this method is accurate to within 0.3° ± 0.2° and 0.8 ± 0.3 mm for helical axis rotation and translation. Euler rotations were referred to the anatomic axes of flexion–extension, radioulnar deviation, and pronosupination. For the intact wrists, motion of the capitate relative to the lunate (midcarpal joint), the lunate relative to the radius (radiocarpal joint), and the capitate relative to the radius (overall wrist joint motion) were calculated. After PRC, motion of the capitate relative to the radius (new radiocarpal joint and overall wrist motion) was calculated for each wrist. For radial deviation, impingement of the carpus on the radial styloid was qualitatively examined in the CT scan of each wrist. The impinging carpal bone was noted and was plotted in 3D for a representative specimen. Two-way analysis of variance was used to detect statistical differences between rotations for each position after PRC with a p value less than .05 considered statistically significant. Carpal postures in each wrist position for a representative specimen were plotted in 3D for purposes of qualitative visualization.

<table>
<thead>
<tr>
<th>Relative Carpal Motion</th>
<th>Flexion</th>
<th>Extension</th>
</tr>
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<tbody>
<tr>
<td>Radiocapitate PRC</td>
<td>PHI, °</td>
<td>D, mm</td>
</tr>
<tr>
<td>49 ± 7</td>
<td>−1.5 ± 1.6</td>
<td>35 ± 12</td>
</tr>
<tr>
<td>Capitolunate intact</td>
<td>35 ± 10*</td>
<td>0.0 ± 0.6</td>
</tr>
<tr>
<td>Radiolunate intact</td>
<td>36 ± 9*</td>
<td>−1.4 ± 1.0</td>
</tr>
<tr>
<td>Intact wrist motion</td>
<td>68 ± 12*</td>
<td>0.4 ± 0.7</td>
</tr>
</tbody>
</table>

Values shown represent rotation (PHI) around and translation (D) along the instantaneous axis of motion (helical axis) for the wrist held in flexion and extension. Radiocapitate joint motion is presented for the wrist after PRC. For the intact wrist, overall wrist motion (capitate motion relative to the radius), capitolunate, and radiolunate joint motion are presented.

*p < .05 compared with radiocapitate motion after PRC.
Results

After PRC, the capitate articulated within the lunate fossa for all positions tested (Fig. 2). Comparing helical axes rotations, overall wrist motion significantly decreased 28% for flexion and 30% for extension (Table 1). Flexion and extension, however, increased 140% (p < .05) and 146% (p = .06), respectively, at the radiocarpal joint after PRC compared with in the midcarpal joint in the intact wrist. Flexion and extension at the radiocarpal joint after PRC increased 136% (p < .05) and 135% (p = .12), respectively, compared with the radiocarpal joint in the intact wrist. The Euler angle rotations followed similar trends as the helical axis rotations in the directions of flexion and extension (Table 2). During flexion–extension, motion of the capitate in the midcarpal joint for the intact wrists and in the lunate fossa after PRC remained primarily rotational with little translation of the point of contact of the capitate seen qualitatively, visible on the posteroanterior and lateral views shown in Figure 3. Further, the helical axis of rotation of the capitate in the midcarpal joint (intact wrists) and radiocarpal joint (PRC wrists) was seen near the center of the spherically shaped capitate head (Fig. 3), indicating pure rotation about this center.

For ulnar deviation, there was a 12% decrease in overall wrist motion after PRC that was not statistically significant (p = .54). After PRC, there was a significant decrease of 40% in radial deviation (Table 3). Radial and ulnar deviation at the radiocarpal joint after PRC decreased by 50% (p < .05) and 14% (p = .45), respectively, compared with radial and ulnar deviation at the midcarpal joint in the intact wrists. Compared with the radiocarpal joint in the intact wrist, radial deviation at the radiocarpal joint after PRC increased by 40% (p = .19), but ulnar deviation did not increase. As evidenced by the Euler angle data, radioulnar deviation in the intact wrist was dominated by motion of

Figure 3. Overall wrist and midcarpal motion seen in the intact wrist during flexion–extension consisted of flexion–extension of the lunate in the radiocarpal joint and flexion–extension of the capitate in the midcarpal joint. In the intact wrist, the point of contact of the capitate in the midcarpal joint did not translate, and the axis of rotation of the capitate in the midcarpal joint was seen near the center of the spherically shaped capitate head (axis of rotation for the capitate in midcarpal joint shown as 3D arrow). Radiocarpal motion in the PRC wrist consisted of flexion–extension only, with little sliding seen of the point of contact of the capitate head in the lunate fossa (lateral view). The axis of rotation of the capitate in the radiocarpal joint remained near the center of the spherically shaped capitate head (shown as 3D arrow). The capitate in flexion is shaded darker and is further designated by the solid black arrow. PA, posteroanterior.
the capitate in the midcarpal joint, supported by flexion and extension of the lunate (Table 3). The flexion and extension of the lunate in the intact wrist is evident in Figure 4. In radioulnar deviation, radiocarpal motion was primarily radioulnar after PRC, whereas radiocarpal motion was primarily flexion–extension in the intact wrists. In the intact wrists in radioulnar deviation, motion of the capitate in the midcarpal joint was only rotational, with little translation of the point of contact of the capitate in the midcarpal joint and a helical axis for rotation of the capitate in the midcarpal joint passing through the spheric head of the capitate (Fig. 4). In radioulnar deviation after PRC, however, the helical axis for rotation of the capitate in the radiocarpal joint moved distal to the center of the spheric head of the capitate (Table 4), indicating that motion at the radiocarpal joint was a combination of sliding of the point at which the capitate contacted the lunate fossa and rotation of the capitate. Qualitatively, the point of contact of the capitate in the lunate fossa moved radially in ulnar deviation toward the ulnar side of the lunate fossa and in radial deviation toward the radial side of the lunate fossa (Figs. 2, 4). In addition, during radial deviation the trapezoid impinged on the radial styloid, limiting the maximal radial deviation achieved for all specimens (Fig. 5).

Helical axis displacements were small, ranging from 0 to 2.2 mm for all cases (Table 4). This indicates that from the reference point of an instantaneous center of rotation, the motions consisted mainly of rotation without much displacement along this axis. This viewpoint, however, does not show how the joint surfaces contact and

![Intact Wrist and PRC Wrist](image)

**OVERALL WRIST MOTION MIDCARPAL MOTION RADIOCARPAL MOTION**

**Figure 4.** Overall wrist and midcarpal motion seen in the intact wrist during radioulnar deviation consisted of flexion–extension of the lunate in the radiocarpal joint and combined flexion–extension and radioulnar deviation of the capitate in the midcarpal joint. In the intact wrist, the point of contact of the capitate in the midcarpal joint did not translate, and the axis of rotation of the capitate in the midcarpal joint was seen near the center of the spherically shaped capitate head (axis of rotation for the capitate in midcarpal joint motion shown as 3D arrow). Radiocarpal motion in the PRC wrist changed to radioulnar deviation only with translation of the point of contact of the capitate head from the ulnar to the radial side of the lunate fossa (seen best on the posteroanterior view). Translation of the contact point seen in the PRC wrist was accompanied by an axis of rotation for the capitate in the radiocarpal joint that was located in the capitate body, distal to the head of the capitate (shown as 3D arrow). The capitate in radial deviation is shaded darker and is further designated by the solid black arrow. PA, posteroanterior.
translate relative to one another; translation or sliding of the capitate head in the lunate fossa was qualitatively increased in radioulnar deviation after PRC compared with capitate motion in the midcarpal joint in the intact wrists (Fig. 4).

Discussion
In this study we successfully used a cadaveric model to investigate the biomechanics after PRC with non-invasive medical imaging. The flexion–extension arc of 84° and radioulnar deviation arc of 43° obtained in this study are comparable with results published for clinical outcomes by Cohen and Kozin and DiDonna et al. Similarly, we found decreased wrist ROM with minimal losses in ulnar deviation and the greatest losses in radial deviation, in agreement with these prior studies.

After PRC, ulnar deviation was relatively maintained, whereas a significant loss was seen in radial deviation. Ulnar deviation may have been maintained because of the ulna-neutral variance and the distally sloped hamate limiting impingement of the carpus on...
the ulna. In addition, the vacated space within the scaphoid fossa may allow radial translation of the capitate in ulnar deviation, decreasing the likelihood for impingement of the hamate on the ulna. In radial deviation, the trapezoid was found to impinge on the radial styloid. This may occur differently in vivo after healing and with neuromuscular control of the wrist motor tendons. In our cadaver model, the trapezium did not contact the radius because it was lying volar to the styloid (Figure 5). In the intact wrist, the carpus allows for radial deviation despite the inclination of the radius by flexion of the proximal carpal row. This allows the scaphoid, trapezium, and trapezoid to clear the radial styloid.

Relative motion at the radiocarpal joint changed after PRC. For the intact wrist, the motion seen at the radiocarpal joint was primarily in the flexion–extension axis during both flexion–extension and radioulnar deviation. After PRC, the motion of the capitate in the radiocarpal joint was in the flexion–extension axis and the radioulnar axis during flexion–extension and radioulnar deviation, respectively. In addition to a change in the direction, the contact motion of the capitate in the radiocarpal joint for radial and ulnar deviation changed from primarily rotational to a combination of both translation and rotation. This change in the type of motion was not seen for flexion and extension, and it may be related to a greater mismatch in the radius of curvature between the head of the capitate and the lunate fossa during radioulnar deviation. Imbriglia et al previously showed that there was a greater difference in the radius of curvature in the radioulnar axis compared with the flexion–extension axis, which correlates with the more distal helical axis in radioulnar deviation compared with flexion–extension for the radiocarpal joint we observed in the PRC wrist. Our results show that the capitate articulated within the lunate fossa throughout the study, and qualitatively the point of contact moved radioulnarily in radioulnar deviation. These observations are also in agreement with the findings of Hogan et al, who used pressure-sensitive film to examine carpal contact after PRC.

Although wrist ROM decreased after PRC, motion of the capitate in flexion–extension increased after PRC (the capitate moved more in the new radiocarpal joint than it had in the midcarpal joint before PRC). In radioulnar deviation, the capitate moved less after PRC, because the motion of the intact wrists during radioulnar deviation was dominated by the midcarpal

| Table 2. Euler Rotations for Flexion and Extension |
|---------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Relative Carpal Motion          | FEM    | RUD    | PROSUP | FEM    | RUD    | PROSUP |
| Radiocapitate PRC              | 48 ± 7 | −3 ± 4 | 11 ± 3 | −32 ± 14 | 2 ± 5 | −5 ± 4 |
| Capitolunate intact            | 22 ± 19* | 0 ± 9 | 7 ± 21 | −15 ± 11* | 6 ± 5* | −3 ± 16 |
| Radiolunate intact             | 34 ± 9* | −13 ± 4* | 6 ± 4 | −26 ± 13 | −1 ± 4 | −2 ± 3 |
| Intact wrist motion            | 68 ± 12* | −4 ± 6 | 10 ± 5 | −50 ± 12* | 3 ± 2 | 2 ± 3 |

Values shown represent rotation in degrees (±SD) for motion in the flexion/extension (FEM) axis (negative values represent extension), radial/ulnar deviation (RUD) axis (negative values represent ulnar deviation), and the pronation/supination (PROSUP) axis (negative values represent pronation) for the wrist held in flexion and extension. Radiocapitate joint motion is presented for the wrist after PRC. For the intact wrist, overall wrist motion (capitate motion relative to the radius), capitolunate, and radioluente joint motion are presented.

| *p < .05 compared with radiocapitate motion after PRC. |

| Table 3. Euler Rotations for Radial and Ulnar Deviation |
|---------------------------------|--------|--------|--------|--------|
| Relative Carpal Motion          | Radial Deviation, ° | Ulnar Deviation, ° |
| Radiocapitate PRC              | −1 ± 6 | 12 ± 5 | 1 ± 3 | 1 ± 9 | −28 ± 7 | −2 ± 5 |
| Capitolunate intact            | −2 ± 8 | 19 ± 8* | −3 ± 4* | 24 ± 22* | −20 ± 10 | 2 ± 9 |
| Radiolunate intact             | 9 ± 4* | 3 ± 2* | 1 ± 2 | −26 ± 10* | −12 ± 5* | −4 ± 4 |
| Intact wrist motion            | 1 ± 5 | 22 ± 6* | 4 ± 4* | 3 ± 8 | −33 ± 10 | −4 ± 6 |

Values shown represent rotation in degrees (±SD) for motion in the flexion/extension (FEM) axis (negative values represent extension), radial/ulnar deviation (RUD) axis (negative values represent ulnar deviation), and the pronation/supination (PROSUP) axis (negative values represent pronation) for the wrist held in radial and ulnar deviation. Radiocapitate joint motion is presented for the wrist after PRC. For the intact wrist, overall wrist motion (capitate motion relative to the radius), capitolunate, and radioluente joint motion are presented.

*p < .05 compared with radiocapitate motion after PRC.
The adept technical assistance of Kitty Stabile is gratefully acknowledged.

Table 4. Helical Axis Motion for Radial and Ulnar Deviation

<table>
<thead>
<tr>
<th>Relative Carpal Motion</th>
<th>Radial Deviation</th>
<th>Ulnar Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PHI, °</td>
<td>D, mm</td>
</tr>
<tr>
<td>Radiocapitate PRC</td>
<td>14 ± 3</td>
<td>−0.1 ± 0.7</td>
</tr>
<tr>
<td>Capitolunate intact</td>
<td>21 ± 7*</td>
<td>0.6 ± 0.3</td>
</tr>
<tr>
<td>Radiolunate intact</td>
<td>10 ± 3</td>
<td>−0.1 ± 0.4</td>
</tr>
<tr>
<td>Intact wrist motion</td>
<td>23 ± 6*</td>
<td>−0.6 ± 0.6</td>
</tr>
</tbody>
</table>

Values shown represent rotation (PHI) around and translation (D) along the instantaneous axis of motion (helical axis) for the wrist held in radial and ulnar deviation. Radiocapitate joint motion is presented for the wrist after PRC. For the intact wrist, overall wrist motion (capitate motion relative to the radius), capitolunate, and radiolunate joint motion are presented.

*p < .05 compared with radiocapitate motion after PRC.

joint (capitolunate joint). In the intact wrist, the helical axes of rotation for the capitate in the midcarpal joint stayed within the head of capitate, indicating that capitate motion was mainly rotation about the center of the capitate head. After PRC, the helical axis of rotation in flexion–extension remained in the capitate head, with capitate motion consisting of rotation about the center of the capitate head. After PRC, the helical axis of rotation in radioulnar deviation moved distal in the capitate, indicating that capitate motion was rotation about the distal capitate, resulting in sliding and rotation of the capitate head on the distal radius.

This study makes use of previously defined mathematical computations using helical axis and Euler angles to quantitatively define individual carpal kinematics and the changes that occur after PRC. Euler angles are defined relative to an arbitrary coordinate system for each carpal bone; in this study they were defined along the functional coordinates of flexion-extension, radioulnar deviation, and pronosupination, which typically are the axes that clinicians use to define carpal motion. It may not be readily apparent, however, that the carpal rotations defined by the Euler angles for each individual carpal bone are not intended to be linearly additive to equal composite carpal motion as shown in Tables 2 and 3. The Euler angles are best used to compare individual carpal motion during a predefined motion with 2 different conditions, such as PRC and the normal carpus. Hence in this study, the capitate was shown to quantitatively have increased rotation after PRC, which may affect overall contact with the radius.

Helical axis analysis characterizes the position change of a 3D body between 2 positions by defining an axis about which the body rotates and along which it moves. This axis is quite different for each carpal bone even for a specified composite direction of overall wrist motion. That is, the helical axis for the capitate was generally within the direction of overall wrist motion, whereas the helical axis for the lunate in the intact wrist was generally within a flexion-extension axis for both flexion-extension and radioulnar deviation. With this in mind, one would not expect the helical axes of the capitolunate and radiolunate joints to equal composite wrist motion during radioulnar deviation as shown in Table 4, whereas adding them during flexion-extension may approximate composite wrist motion, because their axes of motion are along the same general axis.

The use of cadaveric specimens offered both advantages and disadvantages to the study. Cadaveric samples minimized error by minimizing motion artifact, while allowing for the placement of a registration block that allowed for creation of a consistent reference coordinate system. We applied dynamic muscle forces to position the wrists, but the kinematics were measured between statically held positions, and the muscular control necessary for continuous motion may differ from what we used for static positioning. Although every effort was made to recreate a stable dorsal joint capsule after PRC, we could not recreate the changes that would be seen after healing in human subjects. The motion seen in this study, however, was comparable with previously published clinical results, indicating that differences due to the use of cadavers may be small.

The purpose of this study was to determine the changes in kinematics after PRC. We found that the capitate had to flex and extend more after PRC and that radioulnar deviation was associated with more capitate translational motion. Radiol deviation was restricted by impingement of the trapezoid on the radial styloid. Although overall wrist ROM decreased after PRC, it is sufficient for activities of daily living, as reported by Palmer et al.41
References


