Relevance to Musculoskeletal Conditions. A thorough understanding of three-dimensional (3D) in vivo carpal kinematics may be essential in the diagnosis and treatment of complex disorders of the wrist.

Introduction. Three-dimensional in vivo carpal kinematics have not been previously documented. However, several recent 3D in vitro studies have reported that the scaphoid and lunate move in the same direction but with different magnitudes during wrist flexion and extension [3,4,6]. While in vitro studies are an essential tool for examining the mechanics of the carpus, they can be limited in modeling muscular forces and the effects of tissue repair on carpal mechanics. These studies typically employ invasive marker systems (e.g., pins and staples) which may disrupt soft tissues and alter normal motion. In addition to documenting 3D in vivo kinematics, it is important to address the validity of modeling in vivo mechanics with in vitro studies.

To address these questions, we used a novel, non-invasive technique to measure 3D in vivo kinematics of the wrist [2]. The specific purpose of this study was to evaluate motion of the capitae, scaphoid, and lunate in flexion and extension in healthy individuals and to compare these results with previous cadaver work.

Methods. Both wrists of five healthy male subjects (n = 10) were imaged in five wrist positions covering a range of flexion (+) and extension (-). Institutional Review Board approval and informed consents were obtained prior to subject participation.

Image Acquisition. Wrists were positioned in neutral, -60°, -30°, 30° and 60° using a specially designed positioning jig. Volume images (voxel size: (0.20 x 0.37 x 1 mm)³) from the distal radius through the proximal metacarpals were acquired at each position using Computed Tomography (CT) (HiSpeed Advantage, GE, Milwaukee, WI).

Segmentation of Bone Surfaces. The CT volume images were thresholded and bone surface contours were extracted. All image processing was performed on a Silicon Graphics workstation using Analyze (Biomedical Imaging Resource, Rochester, MN) and MATLAB (Mathworks, Natick, MA). All left wrists were reflected to generate right wrists for comparison.

Kinematic Analysis. Global motion of the radius was corrected by minimizing the mean squared distance between the radial bone surfaces in each position [5]. Kinematic values for the scaphoid, lunate, and capitae were calculated using their centroids and principal moments of inertia [1]. Relative carpal motions were derived assuming a fixed radius and a coordinate system defined by the long axis of the radius (X), an intersecting line through the radial styloid (Z) and the perpendicular to these lines (Y) [3]. The origin was the most distal radial surface along the X axis. Carpal motion was described with helical axes of motion (HAM) variables: rotation about and translation along a unique axis. The HAM rotation was projected onto its HAM axis to describe the components of pronation/supination (X axis), flexion-extension (Y axis), and ulnar/radial deviation (Z axis). Radial-capitate motion was used as an indicator of wrist motion [3,4].

Least-squares linear fits and confidence intervals of one standard deviation were calculated for scaphoid and lunate rotation as a function of capitae rotation in flexion and extension. Specific values for scaphoid and lunate rotation were interpolated from least-squares fits at 30 and 60 degrees of flexion and extension.

Results. Data was successfully acquired for all wrists, however, one subject moved slightly in 60° extension during the scan and the data was excluded. There were no obvious differences between the left and right wrists. Capitate motion did not correlate with protractor readings on the positioning jig (note the scatter in Figure 1).

In all motions, the rotation axis for the scaphoid, lunate and capitae passed through the proximal capitae, roughly parallel to the Y axis. Other motion components were generally less than 5°, although the capitae underwent ~5° pronation in extreme flexion and ~10° ulnar deviation in extreme extension. Translation was minimal for all motions (~ 2.0 mm).

The scaphoid closely tracked wrist rotation in extension, but rotated only 73% as much as the wrist in flexion. This implies that in extension, the relative rotation between the scaphoid and capitae was negligible, whereas in flexion, it accounted for 27% of the total wrist rotation. The lunate rotated 78% as much as the wrist in extension and 49% in flexion, implying that the relative rotation between the lunate and capitae was approximately 22% in extension and 51% in flexion (Figure 1 and Table 1). The relative rotation between the scaphoid and lunate was nearly linear in both flexion and extension and it increased approximately 2.3° for every 10° of wrist rotation.

Figure 1. The scaphoid rotated more than the lunate in both flexion and extension. The solid lines are the least-squares fits for scaphoid (thick) and lunate (thin) rotations. The dotted line is the capitae rotation, which is an indication of wrist rotation.

We found that the in vivo scaphoid and lunate rotations were greater than the in vitro rotations in extension, but were similar in flexion. The in vivo scapho-lunate angle appeared similar to the in vitro angles (Table 1).

Table 1. Percentages of scaphoid and lunate contributions to wrist rotation and the scapho-lunate (SL) angle at two wrist positions. (All references are in vitro studies.)

<table>
<thead>
<tr>
<th>Study</th>
<th>Scaphoid Lunate</th>
<th>SL Angle (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>in vitro</td>
<td>102</td>
<td>78</td>
</tr>
<tr>
<td>[3]</td>
<td>87</td>
<td>59</td>
</tr>
<tr>
<td>[4]</td>
<td>83</td>
<td>50</td>
</tr>
<tr>
<td>[6]</td>
<td>71</td>
<td>59</td>
</tr>
</tbody>
</table>

Discussion. In vivo scaphoid and lunate kinematics demonstrated the same general pattern of flexion and extension as previous in vitro work, however, there were differences in the magnitudes of carpal rotations. In particular, in vivo scaphoid and lunate rotations were greater in extension, implying the intercarpal rotations between these bones and the capitae were much less than in vitro results. This discrepancy may be explained by differences in specimen preparation, muscle forces (e.g. active grip vs. weights on major tendons), capsular loosening post-mortem, or pin/marker implantation.

These in vivo methods are currently being applied to more complex wrist motions including radio-ulnar deviation and circumflexion. In the future, the technology will help to describe normal in vivo carpal kinematics, as well as to analyze conditions that can not be modeled in vitro, such as pathokinematics and healing.

Acknowledgments. This work was funded by NIH grant AR44005. The authors would like to thank Cindy Cobb, RTRCT and Wendy Smith, RTRCV for help in acquiring the CT images.


**Dept. of Orthopedics, Yale University School of Medicine, New Haven, CT"