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In Vivo Kinematics of the Scaphoid, Lunate, Capitate, and Third Metacarpal in Extreme Wrist Flexion and Extension

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Abstract

Purpose—Insights into the complexity of active *in vivo* carpal motion have recently been gained using 3D imaging; however kinematics during extremes of motion have not been elucidated. The purpose of this study was to determine motion of the carpus during extremes of wrist flexion and extension.

Methods—Computed tomography scans of 12 healthy wrists were obtained in neutral-grip, extreme loaded flexion, and extreme loaded extension. Three-dimensional bone surfaces and 6-degree-of-freedom kinematics were obtained for the radius and carpal bones. The flexion and extension rotation from neutral-grip to extreme flexion and extreme extension of the scaphoid and lunate was expressed as a percentage of capitate flexion and extension and then compared to previous studies of active wrist flexion and extension. We also tested the hypothesis that the capitate and third metacarpal function as a single rigid body. Finally, joint space metrics at the radiocarpal and midcarpal joints were used to describe arthrokinematics.

Results—In extreme flexion, the scaphoid and lunate flexed 70% and 46% of the amount the capitate flexed, respectively. In extreme extension, the scaphoid extended 74% and the lunate extended 42% of the amount the capitates extended, respectively. The third metacarpal extended 4° farther than the capitate in extreme extension. The joint contact area decreased at the radiocarpal joint during extreme flexion. The radioscapoid joint contact center moved onto the radial styloid and volar ridge of the radius in extreme flexion from a more proximal and ulnar location in neutral.

Conclusions—The contributions of the scaphoid and lunate to capitate rotation were approximately 25% less in extreme extension compared to wrist motion through an active range of motion. More than half the motion of the carpus when the wrist was loaded in extension occurred at the midcarpal joint.

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Clinical Relevance—These findings highlight the difference in kinematics of the carpus during at the extremes of wrist motion, which occur during activities and injuries, and give insight into the possible etiologies of the scaphoid fractures, interosseous ligament injuries, and carpometacarpal bossing.

Keywords

Carpal; Kinematics; Lunate; Passive; Scaphoid

INTRODUCTION

The *in vivo* 3-dimensional kinematic patterns of the carpal bones during active wrist extension and flexion are well documented and have been shown to be consistent across people [1–5]. However, the wrist can also be loaded in extreme extension or extreme flexion [6, 7], and the corresponding kinematic patterns of the carpal bones have not been determined. Studying carpal bone kinematics at the extremes of motion may be important because the carpal ligaments are likely to be strained and injuries are more likely to occur in these positions.

Extreme loaded extension is a common wrist position in occupational settings (carpentry, plumbing), sports activities (push-up, yoga, Pilates, gymnastics), and activities of daily living (opening heavy door, supporting body weight while leaning) [8]. The wrist also achieves this posture during a fall onto an outstretched hand [6, 9, 10]. While extreme loaded flexion is less frequently achieved than extreme extension during normal physiologic motion, certain manual occupational activities or playing string instruments require the wrist to be maintained in an acutely flexed position.

The carpal bones follow consistent kinematic patterns through 60° of wrist flexion and 60° of extension [2, 3, 11–14]. Averaged together, 3-dimensional studies report that the scaphoid flexes 70% and the lunate flexes 45% of the amount the capitate flexes during wrist flexion. In extension, the scaphoid and capitate extend nearly as a single rigid body, while the lunate extends approximately 65% the amount the capitate extends. Furthermore, it is well documented that the third metacarpal and capitate are normally tightly bound throughout this range of wrist motion [15, 16].

Arthrokinematics, as opposed to standard kinematics analysis of whole bones, pertains to the movement of bone surfaces in a joint. Measures of arthrokinematics include the joint contact area and center. Joint contact area describes the area on the subcondral bone surface that is within a threshold distance from a mating bone surface. The center of this area is weighted by the distances within the joint contact area and is mathematically similar to the center of pressure. Combining arthrokinematics with standard kinematics may provide a more thorough understanding of the carpal mechanism because these measures can thoroughly describe kinematic changes and the effects of loading at the joint surfaces.

Studying kinematic and joint space changes of the carpus during extreme passive motions should advance our understanding of common injury patterns that occur during these positions and identify deviations from active wrist kinematics. Therefore, the purpose of this study was to describe the kinematic patterns of the scaphoid, lunate, and capitate when the wrist was passively loaded at the extremes of motion. We describe these patterns using a full 3-dimensional analysis, in terms of percentage of capitate rotation and using arthrokinematics. Our expectation was that the percentage of rotation of the scaphoid and lunate to rotation of the capitate would differ between active and extreme loaded motions. Additionally, we tested the following hypotheses: the capitate and third metacarpal will behave as a single rigid body at the extremes of motion and the joint contact area and center

of the radiocarpal and midcarpal joints will differ at extreme flexion and extension compared to the neutral position.

METHODS

Scanning Protocol

Following institutional review board approval and informed consent, an orthopedic hand surgeon screened 6 right-handed volunteers (6 men, 6 women; mean age 25 ± 4 years) with posterior-anterior and lateral radiographs and physical examination to confirm the lack of injury or diseases that could affect carpal motion. We obtained computed tomography(CT) volume images of the wrist during 3 tasks: neutral-grip, extreme flexion, and extreme extension. The volunteers positioned themselves prone on the CT table (chest supported with a pillow) with their forearms pronated and their right arms extended, in neutral shoulder abduction, and parallel with the center axis of the CT gantry. Wrist position was not constrained.

CT volume images were acquired with a GE LightSpeed 16 CT scanner (General Electric, Milwaukee, WI) at tube settings of 80kVp and 80 mA, slice thickness of 0.6 mm, and a field of view that yielded an in-plane resolution of $0.3 \text{ mm} \times 0.3 \text{ mm}$. During the neutral-grip scan, subjects held a plastic dowel (diameter 28 mm) with a relaxed grip and the forearm flat to the bed of the scanner. We required that the carpus was loaded such that it moved beyond the active range of motion. Therefore, we obtained extreme loaded extension by instructing the patients to maintain an extended elbow and apply approximately 98 N by pushing with the palm of their hand against an analog weight scale that was oriented vertically and fixed to the scanner table (Figure 1). Due to scarce data on acceptable *in vivo* load values, the load of 98 N was chosen to be consistent with the loaded condition reported in previous cadaveric studies [17–19]. Extreme loaded flexion is not a load bearing position; therefore, in the interest of safety, subjects were not required to maintain a target load. Instead, subjects achieved extreme loaded flexion by placing the dorsal aspect of the hand flat to the scale, and extending their arm to passively flex their wrist until they felt slight discomfort in their wrist.

Image Processing and Kinematics

An established markerless bone segmentation and registration method [20, 21] generated bone surface models and 6-degree-of-freedom kinematic transforms for the third metacarpal (MC3), capitate, scaphoid, lunate, and radius. We segmented the bone surface models from the neutral-grip CT volume image using Mimics 9.11 (Materialize, Leuven, Belgium). Custom C++ (GNU gcc, Free Software Foundation, Boston, Massachusetts), and Matlab (The MathWorks, Natick, Massachusetts) code calculated the kinematic transformation of each bone independently from neutral-grip to extreme flexion and to extreme extension [21].

Kinematic variables were described with respect to a radial coordinate system (RCS) [22,23]. The proximally directed X-axis defined pronation-supination. The radially directed Y-axis defined the flexion-extension axis, and the volarly directed Z-axis defined ulnar-radial deviation. The origin of the RCS was located at the intersection of the radiocarpal surface of the radius and the X-axis. Wrist flexion-extension and radial-ulnar deviation positions were defined by the orientation of the long axis of the third metacarpal with respect to the RCS [22].

The rotations and translations of the individual carpal bones from neutral-grip to extreme flexion and extension were described using helical axis of motion variables. The helical axis of motion fully describes the 3-dimensional kinematics of a rigid body by defining a unique rotation axis about which the body rotates and translates. The location of the rotation axis is

described here as its point of intersection with the sagittal plane (X-Z) of the RCS. The X-coordinate of this point of intersection corresponded to the proximal-distal location and the Z-coordinate corresponded to the volar-dorsal location.

Scaphoid and Lunate Rotation

The rotation of the scaphoid and lunate was computed as a percentage of capitate rotation. The percentage described each bones contribution to capitate rotation. It was computed by multiplying the slope of a regression line by 100. The regression line independently fit each bone's rotation from neutral-grip to extreme flexion and neutral-grip to extreme extension as a function of capitate flexion and extension [14].

Arthrokinematics

Joint contact area and center were examined between the radioscaphoid, radiolunate, scaphocapitate, and capitollunate joints. The surface mesh of each bone model consisted of vertex points and triangular connections. Joint contact area on each bone was computed as the area of all triangles that were located within a threshold distance of 2.5 mm or less from the opposing joint surface. The threshold value of 2.5 mm was selected because it approximately captured the entire articular surface of the joints in a neutral posture in this study (Figure 2) [24]. Each triangle within the joint contact area was assigned a weight that was proportional to its area and inversely proportional to its distance from the neighboring bone. The joint contact center was computed as the central point of the weighted triangles included in the contact area. In other words, the contact center was biased toward locations on the articular surface where triangles were closer to the neighboring bone. Contact area was computed at each wrist position and reported as the percent change from the neutral grip position. The joint contact center was visualized as a point on the bone surface, and its change in location was quantified as the distance from its location in neutral grip. Each joint examined has a pair of contact centers associated with each position, and we differentiated them, for example, as follows: the radius-scaphoid contact center was located on the surface of the radius while the scaphoid-radius contact refers to the contact center located on the surface of the scaphoid.

Statistical analysis

The position of the wrist in neutral-grip, extreme flexion, and extreme extension across all subjects was reported as the average $\pm$ 1 standard deviation. The orientation of the rotation axes of the carpal bones was reported as vector components in the RCS. We defined between-subject variability of the rotation axis as the average angle between each subject's rotation axis and the resultant rotation axis of all subjects. A 2-way repeated measures analysis of variance followed by a Holm-Sidak pairwise comparison method evaluated differences between positions and bones of the location of the rotation axis. The mean and 95% confidence interval described rotation of the scaphoid and lunate. To test our hypothesis that the capitate and third metacarpal behave as a single rigid body, a paired Student t-test compared the magnitudes of flexion-extension rotation. We evaluated deviations of contact area from neutral-grip using a 1-way repeated measures analysis of variance followed by a Holm-Sidak pairwise comparison procedure. Finally, we determined if the contact center was beyond 1 mm of its location in neutral-grip independently, for each articulation, by performing a 1-sample t-test with a hypothetical mean of 1 mm.

RESULTS

The wrist was extended $24^\circ \pm 13^\circ$ in neutral-grip, flexed $92^\circ \pm 8^\circ$ in extreme flexion, and extended $78^\circ \pm 5^\circ$ in extreme extension (Figure 3). The wrist was ulnar deviated in neutral-grip, extreme flexion, and extreme extension ($9^\circ \pm 6^\circ$, $9^\circ \pm 6^\circ$, and $11^\circ \pm 8^\circ$, respectively).

The orientation of the rotation axes of the third metacarpal and capitate from neutral-grip to extreme extension and extreme flexion were within 1% of the flexion-extension axis defined by the RCS (Figure 4, Table 1). The scaphoid and lunate rotation axes were also oriented within 1% of the flexion-extension axis of the RCS when the wrist moved from neutral-grip to extreme flexion. However, the scaphoid and lunate exhibited larger out of plane motions during extreme extension with 4% and 8% deviations from the flexion-extension axis of the RCS respectively. The variability in rotation axis orientation was small, ranging from 5° to 8° (Table 1).

The rotation axes of the scaphoid and lunate from neutral-grip to extreme flexion and from neutral-grip to extreme extension were located near the proximal articular surface of the capitate (Figure 5). They were dorsal to the midpoint of the proximal pole of the capitate in extreme extension and volar to the midpoint in extreme flexion. There were no significant differences ($P = 0.46$) between the locations of the scaphoid and lunate rotation axes in extreme extension. However, in extreme flexion the lunate rotation axis was located an average of 1.4 mm more proximal and an average of 4.6 mm more volar than the scaphoid rotation axis ($P < 0.001$). The third metacarpal rotation axis was located an average 0.9 mm more dorsal ($P < 0.05$) than the capitate in extreme extension.

In extreme flexion, the scaphoid flexed 70% (CI: 66% – 73%) and the lunate flexed 46% (CI: 43% – 49%) of capitate flexion (Figure 6). In extreme extension, the scaphoid extended 74% (CI: 67% – 82%) and the lunate extended 42% (CI: 33% – 50%) of capitate extension. The third metacarpal flexed $1.0 \pm 1^\circ$ ($P < 0.05$) farther than the capitate in extreme flexion and extended $4^\circ \pm 2^\circ$ ($P < 0.001$) farther than the capitate in extreme extension (Table 2).

From neutral-grip to extreme flexion, the radius-scaphoid contact center shifted 5.5 ± 1.0 mm toward the radial styloid and volar ridge of the radius, while in extreme extension it shifted dorsally $2.4 \text{ mm} \pm 1.0 \text{ mm}$ (Figure 7). At extreme flexion, the contact areas of the lunate and scaphoid on the radius decreased $39\% \pm 22\%$ and $66\% \pm 13\%$ ($P < 0.05$), respectively, from their values at neutral grip (Table 3). In extreme extension the contact area of the lunate and scaphoid increased ($P < 0.05$) $45\% \pm 22\%$ and $13\% \pm 16\%$, respectively, from their values at neutral-grip.

The capitate-scaphoid contact center was consistently located on the radial aspect of the proximal pole of the capitate. The scaphoid-capitate contact center shifted $3.3 \text{ mm} \pm 1.0 \text{ mm}$ ($P < 0.05$) toward the distal tubercle of the scaphoid when the wrist was in extreme flexion. The contact centers of the capitate and lunate were located centrally in neutral-grip, volarly in extreme flexion, and dorsally in extreme extension ($P < 0.05$). The contact area consistently increased ($P < 0.05$) from extreme flexion to extreme extension at each articulation of the midcarpal joint (Table 3).

DISCUSSION

This study describes the kinematics of the scaphoid, lunate, capitate, and third metacarpal at extreme wrist flexion and extension. When the wrist is loaded at extremes, wrist position is defined by the position of the forearm and an externally applied load. Several *in vivo* studies have evaluated 3-dimensional wrist postures throughout the range of active motion (approximately 60° F to 60° E) using markerless tracking techniques similar or identical to those used in the present study [2, 13, 14]. These studies of active wrist motion have shown that from neutral to wrist extension, the scaphoid and capitate extend nearly as a single rigid body (range: 86% – 99%) while the lunate extends an average of 64% (range: 63% – 68%) the amount the capitate extends [2, 13, 14]. During extreme loaded wrist extension, however, the scaphoid and lunate extend only 74% (CI: 67% – 82%) and 42% (CI: 33% –

50%) as much as the capitate. We note that the confidence intervals fall outside the range of values reported in the literature. Therefore, the scaphoid and lunate rotate less compared to the capitate during extreme extension but rotate with the capitate in active extension. In active extension, the capitate rotates less than it does in loaded extreme extension (approximately 60° compared to 78°). In order for scaphoid and lunate rotation to be less than the capitate, as seen in active wrist range of motion, their motion must be restricted along the path. We postulate that this restriction occurs between the end range of active motion (when the rotation of the scaphoid and lunate is closer to that of the capitate) and extreme extension when the volar ligaments are maximally strained and the scaphoid impinges on the dorsal ridge of the scaphoid facet. A likely result of this mechanical impingement is unbalanced compensatory forces of the scaphoid by its supporting ligaments. Scaphoid waist fractures or ruptures of the scapholunate ligament may result when these unbalanced forces exceed each structure's ability to withstand them. Although the motion between the third metacarpal and the capitate at extreme extension was small, this may be the etiology of carpal boss formation, as it has been suggested that repetitive excessive motion at this joint can lead to spur formation [25].

In contrast, the contribution of scaphoid and lunate flexion to capitate flexion during extreme flexion was similar to previous *in vivo* reports of active flexion [2, 13, 14]. When combined, these studies report a range of (63% – 73%) and (31% – 46%) for the scaphoid and lunate respectively [2, 13, 14]. We found that the scaphoid flexed 70% (CI: 66% – 73%) and the lunate flexed 46% (CI: 43% – 49%) of capitate flexion. These findings are not surprising given that the dorsal ligamentous restraints are considered to be thin and weak compared to the volar ligaments [23]. Therefore, these ligaments may allow a greater range of motion during wrist flexion before restraining the scaphoid and lunate. Because the volunteers flexed until they felt discomfort, we cannot safely determine whether the wrist is capable of achieving further extreme flexion with subsequent scaphoid and lunate restriction. The third metacarpal flexed only 1° farther than the capitate during extreme flexion. This difference is on the order of our measurement error and unlikely to be clinically significant.

Joint space characteristics were quantified with subchondral bone surface measurements, which do not represent physical contact between adjacent bones. Joint space measurements were used as a surrogate for contact measurements because computed tomography is unable to resolve articular cartilage in the intact joint. They are useful in elucidating which areas on 2 opposing surfaces move closer to one another without the need for cartilage contact estimation. In extreme flexion, the joint contact center of the scaphoid on the radius moved radial and distal, approaching the radial styloid and the volar ridge of the radius. Additionally, the contact area decreased 66% from neutral-grip, suggesting less congruence between the articulating surfaces. We postulate that the lunate follows a smooth rotation (likely because of its highly congruent and nearly hemi-spherical contour) while the scaphoid cantilevers on the volar radial lip.

The rotation axis of the capitate was more proximal in extreme positions compared to its position in the proximal pole during active wrist motion [15, 27, 28]. These findings indicate that in extreme flexion and extension, the capitate begins to rock within the lunate fossa rather than rotating within due to volar and dorsal impingement of the capitate on the lunate during extreme flexion and extreme extension.

The primary limitation of this study is the inference of motion from 3 static positions. The helical axis assumes the motions between the neutral-grip position and those at the end range of flexion-extension are at constant rate and in a single direction. While we can infer the general behavior of the carpal bones as they move from neutral to extreme flexion and

extension, we cannot address any nuances in kinematic patterns during intermediate positions. This study aimed to determine wrist kinematics in extreme loaded positions. While targeting 98 N in extreme extension and requiring loading to resistance in extreme flexion was sufficient to load the wrist, we cannot address differences in wrist kinematics as a function of load. We did not measure active wrist positions in the current study as the patients pushed the palm of their hands against the weight scale. Therefore, we cannot perform a direct statistical comparison between loaded extreme and active motion. We did not constrain wrist position in the radial/ulnar plane during experimentation, nor did we measure extreme radial and ulnar deviation. Our analysis reports that subjects preferred to position their wrists in approximately 10° ulnar deviation during all 3 wrist positions of this study. We postulate this may have been due to subjects attempting to keep their wrist in a more stable position during testing [29] and due to the forearm posture required for central hand placement on the scale at the extremes of motion.

This study of the intact wrist demonstrates that the motion of the carpus when the wrist is loaded in extension shifts toward the midcarpal joint and gives insight into the vulnerability of the scaphoid and scapholunate interosseous ligament to injury in extreme wrist extension. Future studies of extreme wrist positions, when the carpal ligaments are engaged, may provide new insights into ligament function and allow clinicians to optimize treatment strategies.

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Figure 1.
Extreme loaded extension (top) and extreme loaded flexion (bottom).

Figure 2. The 2.5 mm threshold for the radiocarpal joints (left) and midcarpal joints (right) of a representative subject. The 2.5 mm contour captured the entire articular surface when the wrist was in the neutral grip position.

Figure 3.

Wrist flexion and extension of all 12 subjects determined by the third metacarpal with respect to the radius. An image of a radial view of a right wrist is also included, indicating (left) neutral-grip (middle) extreme flexion, and (right) extreme extension. Wrist positions were consistent across subjects with standard deviations of 13°, 8°, and 5° for neutral-grip, extreme flexion, and extreme extension respectively.

Figure 4. Resultant rotation axes of the third metacarpal (MC3) (green) and capitate (yellow) (top) and scaphoid (purple) and lunate (turquoise) (bottom) for wrist motion from neutral-grip (gray) to extreme extension and extreme flexion. The resultant axes were computed from each subject's rotation axis. The translucent cones represent variability in the angle formed by each subject's rotation axis and the resultant axis. The angular variability is calculated from vectors of unit length and is placed at origin of the vector in the figure for illustration purposes.

Figure 5.

Helical rotation axis intersection in the sagittal plane plotted with sagittal outlines of the each subject's radius and capitate in neutral-grip. Red points indicate the location of the rotation axis when the wrist moves from neutral-grip to extreme extension, and blue points indicate the location of the rotation axis when the wrist moves from neutral-grip to extreme flexion.

Figure 6.

Scaphoid, lunate, third metacarpal, and capitate flexion-extension rotation vs. capitate rotation from neutral-grip to extreme flexion and extreme extension. The dotted line represents capitate flexion-extension vs. capitate flexion-extension. During extension, data points below the dotted line indicate the bone is extending less than the capitate. During flexion, data points above the dotted line indicate the bone is flexing less than the capitate. The scaphoid and lunate rotated less than the capitate in both extreme flexion and extreme extension, while the third metacarpal rotated slightly farther than the capitate during extreme flexion and extreme extension.

Figure 7.

The mean (small central sphere) and standard deviation (large sphere) of the location of the joint contact center in all 3 wrist positions. “*” denotes a significant difference ($P < 0.05$) in the contact center location compared to neutral-grip. At the radiocarpal joint (left), as the wrist moved from extreme extension to extreme flexion, the contact area decreased. Note the shift of the radius-scaphoid contact-center toward the radial styloid in extreme flexion. At the midcarpal joint (right), the capitate exhibited a rocking motion on the lunate as it moved from neutral-grip to extreme flexion or extreme extension. Note also, the consistency in the capitate-scaphoid contact center location in all three positions. However, the contact center shifted toward the distal tubercle of the scaphoid in extreme-flexion.

Table 1

Unit vector components describing the orientation of the rotation axis for each bone (third metacarpal (MC3)) from neutral-grip to extreme flexion and extreme extension, reported in the radius-based coordinate system (RCS). X, Y, and Z are the components of pronation/supination, flexion/extension, and ulnar/radial deviation, respectively. Variation with rotation axis was the mean angle between each subject's rotation axis and the resultant rotation axis of all subjects.

Bone	Position	X	Y	Z	Variation With Rotation Axis (°)
MC3	Extension	0.001	-0.996	0.084	8.8
	Flexion	0.038	0.999	-0.025	5.5
Capitate	Extension	-0.003	-0.993	0.115	8.8
	Flexion	0.032	0.999	-0.029	5.3
Scaphoid	Extension	-0.131	-0.957	0.259	5.7
	Flexion	0.012	0.999	-0.019	5.6
Lunate	Extension	-0.070	-0.924	0.376	7.8
	Flexion	0.002	0.986	0.168	6.6

Table 2

Average (1 SD) rotation about and translation along the helical axis from the neutral-grip position. X, Y, and Z correspond to the pronation/supination, flexion/extension axis, and ulnar/radial deviation components, respectively.

Bone	Motion	X		Y		Z	
		rotation (deg)	translation (mm)	rotation (deg)	translation (mm)	rotation (deg)	translation (mm)
MC3	Extension	0.05 (4.0)	0.04 (0.07)	-53.4 (12.7)	0.31 (0.86)	4.5 (8.6)	-0.15 (0.30)
	Flexion	4.7 (8.3)	0.07 (0.07)	115.7 (15.9)	1.2 (1.0)	-2.6 (10.1)	-0.01 (0.11)
Capitate	Extension	-0.13 (3.5)	0.02 (0.07)	-49.5 (13.0)	0.61 (0.67)	5.7 (7.8)	-0.17 (0.27)
	Flexion	3.9 (7.4)	0.05 (0.08)	114.7 (15.7)	1.2 (0.9)	-3.1 (10.4)	-0.01 (0.13)
Scaphoid	Extension	-5.1 (2.5)	0.17 (0.08)	-37.1 (10.7)	1.2 (0.4)	10.1 (4.5)	-0.36 (0.20)
	Flexion	1.0 (5.5)	0.01 (0.08)	79.8 (13.0)	0.79 (0.67)	-1.5 (7.1)	-0.02 (0.08)
Lunate	Extension	-1.6 (1.7)	0.07 (0.09)	-21.0 (8.1)	1.2 (0.4)	8.5 (3.7)	-0.51 (0.25)
	Flexion	0.14 (4.8)	-0.01 (0.2)	52.6 (10.1)	1.9 (0.7)	8.9 (5.2)	0.36 (0.25)

Table 3

Percent increase or decrease of the contact area from neutral-grip at the radiocarpal and midcarpal joints, and distance of the contact center from neutral-grip (Figure 7).

Joint	Bone	% Change in Contact Area		Change in Contact Center (mm)	
		Neutral-Grip to Flexion	Neutral-Grip to Extension	Neutral-Grip to Flexion	Neutral-Grip to Extension
Radiolunate	Radius	-40.0 (22.0) *	45.3 (21.6) *	3.9 (1.8) *	1.8 (0.7) *
	Lunate	-45.2 (19.0) *	46.6 (26.2) *	7.0 (3.0) *	2.5 (1.3) *
Radioscaphoid	Radius	-65.5 (12.6) *	13.2 (16.1) *	5.5 (1.0) *	2.4 (1.0) *
	Scaphoid	-62.4 (14.6) *	23.3 (26.1) *	8.0 (1.8) *	5.2 (1.2) *
Lunocapitate	Lunate	-9.1 (10.4)	7.2 (6.2)	3.0 (1.4) *	1.5 (0.5) *
	Capitate	-1.7 (13.8)	13.6 (10.1) *	7.7 (1.2) *	3.3 (1.2) *
Scaphocapitate	Scaphoid	-22.9 (0.5) *	9.4 (4.3) *	3.3 (1.0) *	0.8 (0.5)
	Capitate	-23.4 (10.3) *	15.3 (6.7) *	2.4 (0.6) *	1.5 (0.6) *

Mean ($\pm$ SD).

* Indicates a statistical significant ($P < 0.05$) from neutral-grip.