Biomechanical Evaluation of Carpal Kinematics during Simulated Wrist Motion

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Abstract

Background Flexion and extension of the wrist is achieved primarily at the radiocarpal and midcarpal joints. Carpal kinematics have been investigated, although there remains no consensus regarding the relative contribution of each bone to wrist motion.
Purpose To determine the kinematics of the scaphoid, lunate, and capitate during unconstrained simulated wrist flexion/extension and to examine the effect of motion direction on the contribution of each bone.
Materials and Methods Seven cadaveric upper extremities were tested in a passive wrist simulator with 10N tone loads applied to the wrist flexors/extensors. Scaphoid, lunate, and capitate kinematics were captured using optical tracking and analyzed with respect to the radius.
Results Scaphoid and lunate motion correlated linearly with wrist motion ($R^2 = 0.99$, 0.97). In extension, the scaphoid and lunate extended 83 ± 19% and 37 ± 18% relative to total wrist extension ($p = 0.03$, 0.001), respectively. In flexion, the scaphoid and lunate flexed 95 ± 20% and 70 ± 12% relative to total wrist flexion ($p = 1.0$,0.01) , respectively. The lunate rotated 46 ± 25% less than the capitate and 35 ± 31% less than the scaphoid. The intercarpal motion between the scaphoid and lunate was 25 ± 17% of wrist flexion.
Conclusion The scaphoid, lunate, and capitate move synergistically throughout planar wrist motion. The scaphoid and lunate contributed at a greater degree during flexion, suggesting that the radiocarpal joint plays a more critical role in wrist flexion.
Clinical Relevance The large magnitude of differential rotation between the scaphoid and lunate may be responsible for the high incidence of scapholunate ligament injuries. An understanding of normal carpal kinematics may assist in positioning carpal bones during partial wrist fusions and in developing more durable wrist arthroplasty designs.

Keywords
- carpal bone
- kinematics
- wrist
- scaphoid
- lunate

Normal wrist kinematics rely on the intricate interplay between the articular geometry and ligamentous constraints. The wrist joint is frequently subdivided into the radiocarpal and midcarpal joints based on the functional grouping of the bones in the proximal and distal rows.[1] The midcarpal joint is formed by the articulation of the scaphoid, lunate, and

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triquetrum with the trapezium, trapezoid, capitate, and hamate.[2] The radiocarpal joint is formed by the articulation between the bones of the proximal carpal row, the scaphoid, lunate, and triquetrum with the distal radius. The combination of midcarpal and radiocarpal joint motion is responsible for the total range of wrist motion in flexion and extension.[3]

Carpal kinematics have been previously studied, yet there remains no consensus regarding each carpal bone's contribution to wrist motion. This disparity has led to numerous theories depicting the normal kinematics of the wrist, including row, column, intercalated segment, and oval ring concepts.[1,4–6] In addition, previous kinematic studies have investigated the contribution of the radiocarpal and midcarpal joints during wrist motion; however, there is disagreement regarding the role of each joint throughout flexion and extension.[3,7–10] A more detailed understanding of normal carpal bone kinematics during wrist motion is necessary to effectively diagnose and treat ligamentous injuries of the wrist. This information is also clinically beneficial as many injuries arising in the wrist often manifest as an alteration of intercarpal motion.[11] Furthermore, a better understanding of carpal kinematics allows for evaluation of the wrist joint under normal and pathological conditions and should lead to improvements in the outcome of partial wrist fusions, ligament reconstructions, and prosthetic devices.[12]

The objective of this in vitro biomechanical study was to determine the kinematics of the scaphoid, lunate, and capitate during planar motions of unconstrained wrist flexion and extension. In addition, this study examined the effect of motion direction (i.e., flexion or extension) on kinematics and the contribution of scaphoid and lunate rotation to overall wrist flexion and extension.

Materials and Methods

Specimen Preparation

Seven fresh frozen cadaveric upper limb specimens (average age: 67 years; range: 37–91; 5 male; 4 left) amputated at the midhumerus were used. Computed tomography scans of each wrist were examined beforehand to rule out underlying wrist pathology. There was no history of trauma or wrist disease in any of the specimens used. The upper limbs were thawed overnight at room temperature, and the fingers were disarticulated at the metacarpophalangeal joints. The tendons of the abductor pollicis longus (APL), extensor carpi radialis brevis (ECRB), extensor carpi radialis longus (ECRL), extensor carpi ulnaris (ECU), flexor carpi radialis (FCR), and flexor carpi ulnaris (FCU) were exposed and sutured at the musculotendinous junction (Ethicon, Somerville, NJ). The specimens were mounted in a wrist motion simulator by rigidly securing the humerus in a clamp (►Fig. 1). Two threaded pins were used to fix the ulna to the simulator with the elbow aligned at 90-degree flexion. A Steinmann pin was inserted into the proximal radius securing the forearm in neutral rotation (►Fig. 1).

The neutral position of the wrist in flexion–extension was defined by visually aligning the third metacarpal with the forearm. As the capitate/third metacarpal joint is rigid, the position of the capitate was used to represent wrist position.[13] A Steinmann pin was inserted longitudinally into the shaft of the third metacarpal and placed into the arc of the simulator as a guide for passive motion (►Fig. 1). Muscle tone loads were produced using pneumatic actuators via cables routed through a system of pulleys and connected to the

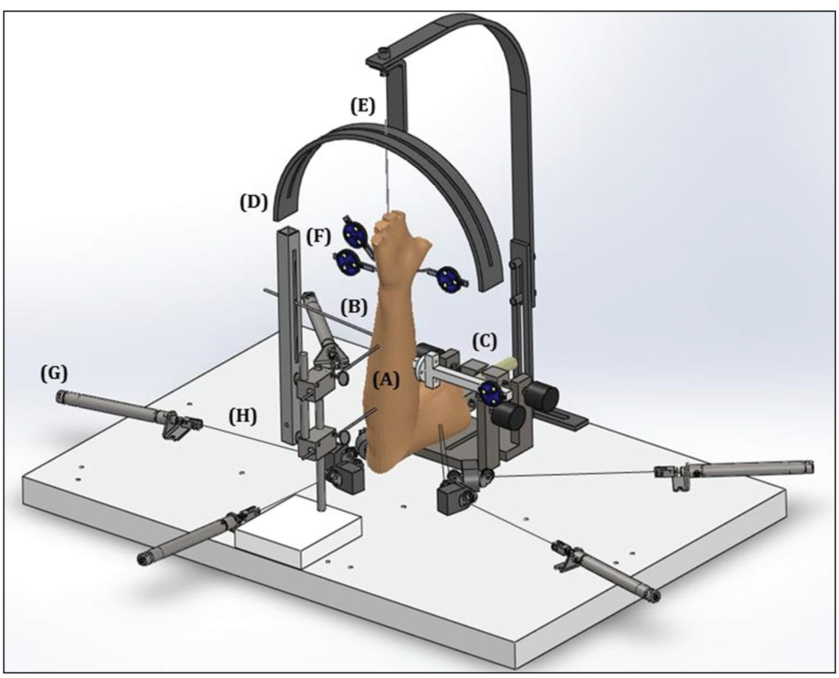

Fig. 1 In vitro passive motion wrist simulator. This device is capable of loading six muscle groups of interest while simulating passive flexion extension or radial ulnar deviation of the wrist. (**A**) Ulna fixed with the elbow at 90-degree flexion. (**B**) Radius fixed with the forearm in neutral rotation. (**C**) Rigidly fixed humerus. (**D**) Flexion/extension motion arc. (**E**) Steinmann pin inserted into third metacarpal; passive motion guide. (**F**) Optotrak Certus 6 degrees-of-freedom tracking markers. (**G**) Pneumatic actuators. (**H**) Cables connecting actuators and corresponding muscle sutures.

tendon sutures (Airport Corporation, Norwalk, CT). Optical tracking markers (Optotrak Certus, Northern Digital, Waterloo, Ontario, Canada) were secured to the lunate, scaphoid, capitate, and radius under fluoroscopic control to capture the kinematics throughout testing. The radial marker was attached to the shaft of the radius. The lunate marker was inserted dorsally through a small arthrotomy along the distal edge of the dorsal radiocarpal ligament, the scaphoid marker was inserted through a small volar incision over the tuberosity, and the capitate marker was placed dorsally.

Testing Protocol

Passive flexion and extension motion of the wrist was simulated by the investigator moving the Steinmann pin along the flexion/extension motion arc of the simulator at a speed of approximately 5 degrees per second. Tone loads of 10 N were applied to the APL, ECRB, ECRL, ECU, FCR, and FCU. Each specimen was subjected to two extension and two flexion trials, and data were analyzed from the second trial of each.

Extension trials were defined as moving the wrist from flexion to extension, and flexion trials were defined as extension to flexion. Kinematic data were extracted in 5-degree increments. The specimens were irrigated with saline, and the skin was closed throughout the testing protocol in an effort to maintain specimen hydration. Data were analyzed from 35 degrees of extension to 35 degrees of flexion due to variable specimen range of motion and impingement of the trackers in some specimens at the extremes of motion. Following the testing protocol, the joints were dissected, and the landmarks on the radius, scaphoid, lunate, and capitate were digitized using a pointed stylus. The neutral position of the wrist, as defined by the International Society of Biomechanics (ISB), served to form the coordinate systems and was used to calculate the angle of wrist flexion and extension.[14]

Outcome Variables and Data Analysis

The angulation of the scaphoid and lunate relative to the distal radius was evaluated for both flexion and extension trials. Extension and flexion trials were averaged over the tested range of motion to calculate the contribution of the lunate and scaphoid to global wrist motion. Wrist flexion extension angle was defined as the angle between the long axis of the radius and the long axis of the third metacarpal with respect to the distal radius coordinate system. The coordinate systems for each bone agreed with ISB recommendations, with the exception of the origin of each of the carpal coordinate systems located at the proximal pole in contrast to the suggested volumetric centroid.[14] However, the orientation of the carpal coordinate systems remained in parallel with the radial coordinate system while the wrist was in neutral position.[14]

Statistical Methods

A three-way repeated measures analysis of variance was completed using SPSS 17.0 (SPSS Inc., Chicago, IL). The factors (viz. independent variables) included direction of motion (flexion, extension), bone (capitate, scaphoid, lunate), and flexion extension angle. A paired sample *t*-test analysis was also performed for the scaphoid and lunate rotational data to assess differences between flexion and extension motion pathways. Statistical significance was set at $p < 0.05$.

Results

Flexion Extension of the Scaphoid and Lunate

The rotation of the scaphoid and lunate was found to correlate linearly with wrist motion during flexion and extension trials (►**Fig. 2**). Scaphoid rotation was an average 95 ± 20% ($R^2 = 0.99$; $p = 1.0$) of wrist flexion, and lunate rotation was an average 70 ± 12% of wrist flexion ($R^2 = 0.99$; $p = 0.007$). The motion between the scaphoid and lunate was 25 ± 17% of global wrist flexion. For 60 degrees of capitate flexion, the scaphoid flexed 57 ± 12 degrees, and the lunate flexed 42 ± 7 degrees, thus yielding scapholunate motion of 15 ± 14 degrees.

Scaphoid rotation was 83 ± 19% ($R^2 = 0.99$; $p = 0.033$) of wrist extension, and lunate rotation was 37 ± 18% ($R^2 = 0.97$; $p = 0.001$) of wrist extension. The motion between the scaphoid and lunate was 46 ± 15% of global wrist extension. For 60 degrees of capitate extension, the scaphoid extended 50 ± 11 degrees, the lunate extended 22 ± 11 degrees, and the scapholunate motion was 28 ± 16 degrees.

Ratio of Scaphoid and Lunate Rotation to Wrist Rotation

The ratio of scaphoid and lunate rotation to global wrist rotation decreased as the wrist was moved from flexion to extension (►**Fig. 3**). There was no significant difference in scaphoid rotation between flexion and extension of the wrist ($p = 0.15$) (►**Fig. 3**). However, there was a significant decrease in lunate rotation compared with wrist rotation from flexion to extension ($p = 0.004$). Significant differences were found between the rotation of the lunate when compared with both the scaphoid and capitate throughout flexion and extension (►**Fig. 4**). The lunate rotated on average 46 ± 25% less than the capitate and 35 ± 31% less than the scaphoid during wrist flexion and extension ($p = 0.001$). The scaphoid rotated on average 11 ± 19% less than the capitate during wrist flexion and extension; however, this was not statistically significant ($p = 0.066$).

Direction of Motion

Direction of motion did not have a statistically significant effect on carpal kinematics for wrist flexion and extension motions with mean differences less than 6.4% between pathways. There was no difference in scaphoid and lunate contributions to wrist flexion or extension ($p = 0.26$ and 0.77, respectively) for the two directions of motion (►**Fig. 5**).

Discussion

Planar wrist flexion/extension is achieved via rotation at the radiocarpal and midcarpal joints and is defined by the motion of the capitate as it moves with respect to the radius. Carpal kinematics have been studied in vivo and in vitro, yet there remains no unanimity regarding the contribution of each carpal bone to wrist motion. This study investigated capitate,

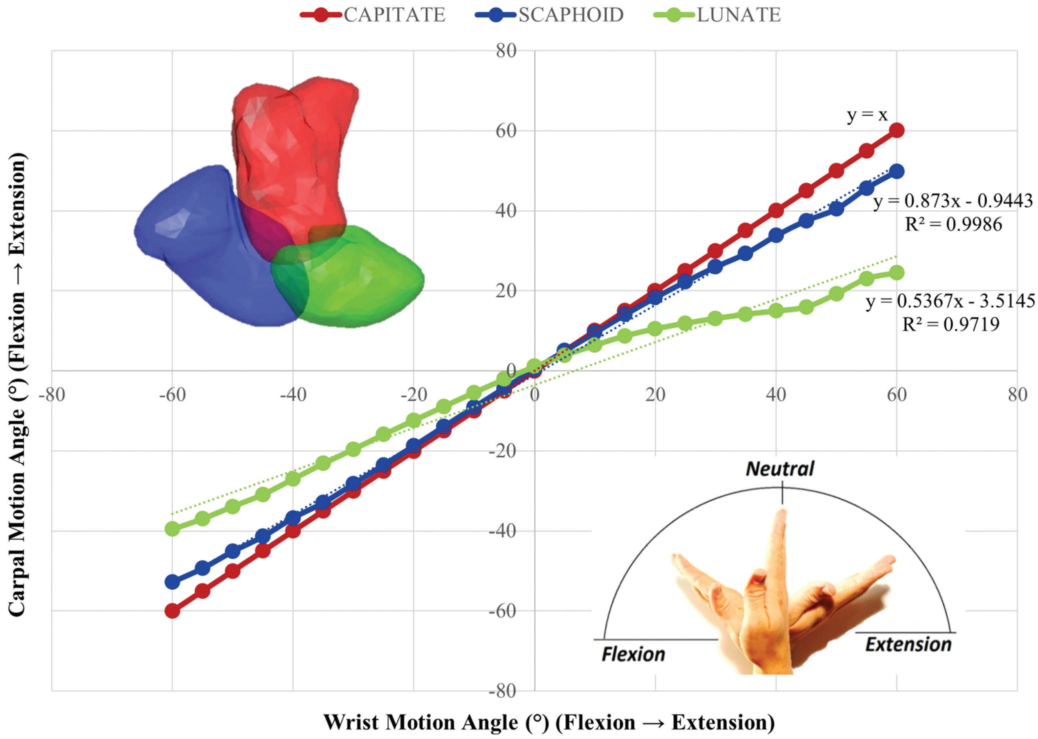

Fig. 2 The mean relative rotation of the scaphoid, lunate, and capitate (with respect to the radius) from 60 degrees of wrist flexion to 60 degrees of extension. Standard deviations were omitted for clarity (scaphoid range: ± 2.20 to ± 5.25 degrees; lunate range: ± 1.01 to ± 5.15 degrees).

scaphoid, and lunate kinematics during unconstrained planar wrist flexion/extension. Our results found that at the radiocarpal joint, the scaphoid contributes at a greater extent to wrist motion throughout flexion/extension when compared with the lunate. Scaphoid and lunate motion was found to correlate linearly with capitate motion throughout the tested range of motion, both contributing more to wrist motion during flexion. Additionally, our results found that the ratio of scaphoid and lunate rotation to wrist rotation decreases from flexion to extension, suggesting that the radiocarpal joint plays a more critical role in flexion. The large magnitude of scapholunate differential rotation may explain the high incidence of scapholunate ligament injuries relative to other intercarpal joints.[15]

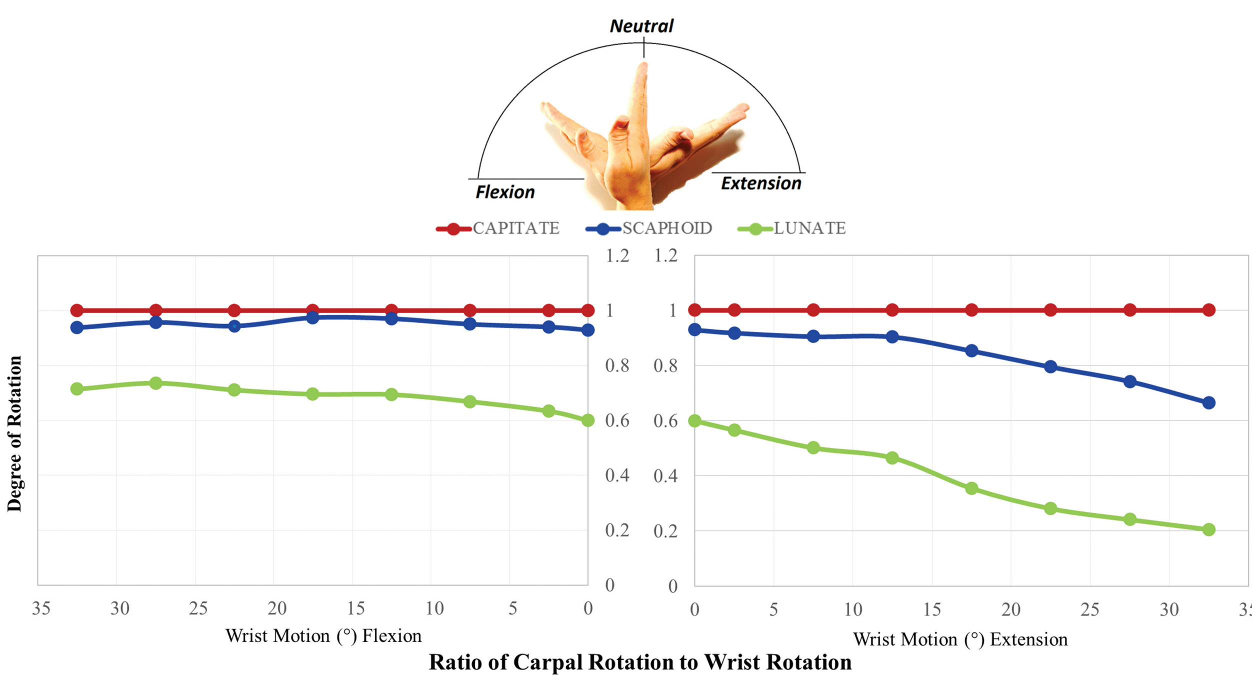

Fig. 3 The ratio of scaphoid and lunate rotation respect to wrist rotation. Standard deviations were omitted for clarity (scaphoid range: ± 0.08 to ± 0.24 degrees; lunate range: ± 0.10 to ± 0.26 degrees).

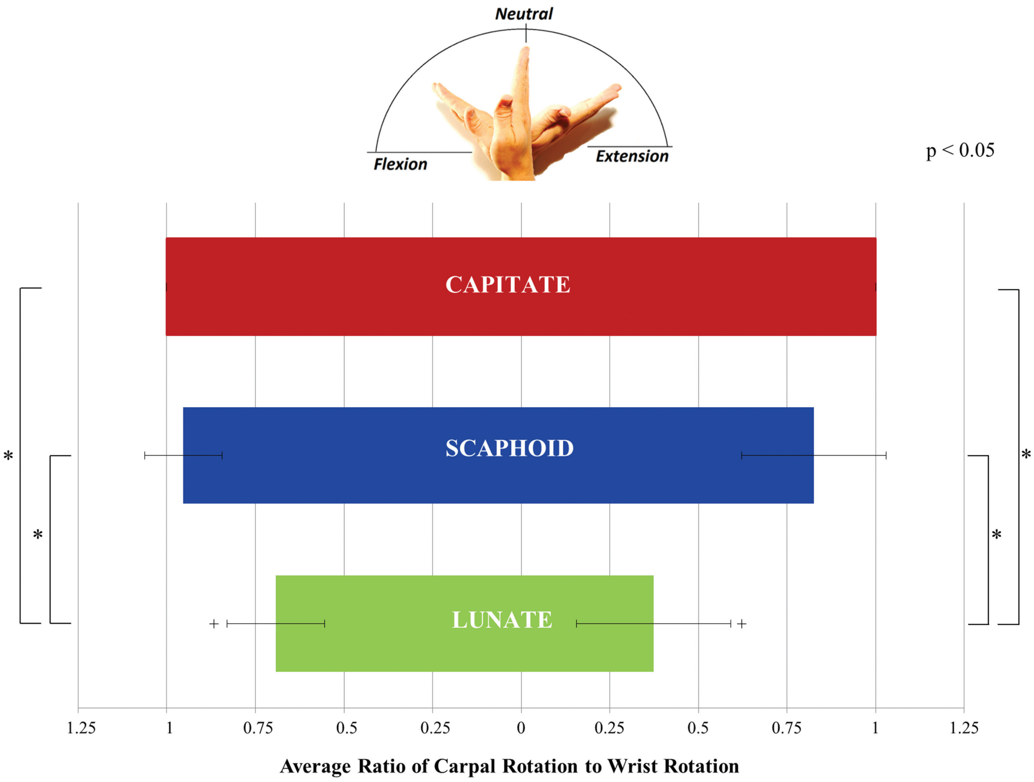

Fig. 4 The mean (±1 std dev) ratio of scaphoid and lunate motion with respect to wrist rotation during flexion and extension. The capitate demonstrates a 1:1 ratio with global wrist rotation, as it is directly in line with the wrist flexion extension axis. The error bars indicate the standard deviation of each carpal bone for both flexion and extension.

At all wrist positions, we found the scaphoid contributed a greater extent to wrist motion compared with the lunate, consistent with previous in vivo and in vitro studies.[16–21] Our results confirm the synergistic motion between the capitate, lunate, and scaphoid throughout motion. Agreeing with Wolfe et al,[20] the present data indicate that the scaphoid and lunate correlate linearly with the capitate throughout wrist flexion/extension (►**Fig. 2**). Our findings are also consistent with Werner et al,[19] who showed that the scaphoid and lunate do not contribute equally to wrist flexion and extension, each producing a unique arc of motion (►**Fig. 2**). Despite finding minor interspecimen variability, we confirmed wrist motion during flexion and extension follows a similar trend. This supports the hypothesis by Kobayashi et al[16] that the underlying mechanism that governs carpal kinematics in the uninjured state is uniform within subject population.

Contrasting the majority of published studies, we found the scaphoid contributed more to flexion compared with extension (flexion 95%, extension 83% vs. flexion 86% flexion, extension 69%).[17] Likewise, our results for the lunate contrast the range of contributions found within literature for flexion, which are larger than the average of previously reported contributions (70 vs. 50%),[17] but agree for extension. As shown by Moojen et al, a large variability exists in previously reported scaphoid and lunate contributions to wrist motion due to methodologies limitations (scaphoid extension range: 58–99%, flexion range: 61–88%; Lunate extension range: 22–68%; flexion range: 36–63%).[17] Previous in vitro studies[7,12,19,22] were limited to less than ± 60 degrees flexion/extension due to tracking constraints and assumed a linear relationship within these positions similar to this study. The in vivo study performed by Wolfe et al[21] used static positioning at four positions of flexion/extension, while an in vivo study by Moojen et al[17] imitated continuous motion using 5-degree increments. The present investigation provides new information on continuous wrist motion.[23]

Previous kinematic studies have reported varying results regarding the relative contribution of the radiocarpal and midcarpal joints to wrist motion, with few studies showing equal radiocarpal and midcarpal contribution during flexion, with the radiocarpal joint contributing more in extension.[24–26] Other studies suggested that the radiocarpal joint contributes a greater degree in wrist extension and the midcarpal joint more in flexion.[3,8,18,27,28] Agreeing with our study, several investigators showed that the radiocarpal joint contributed more in wrist flexion and the midcarpal joint contributed more in extension.[22,29–31] This variability may stem from how carpal angles were represented—either relative to a starting position or similar to this study, as an angle relative to another bone.[23] Reporting carpal angles with respect to the distal radius gave an anatomical reference throughout the tested range of motion.

Currently, a range of surgical options exist for wrist arthritis, including partial carpal fusions[32]; however, it is unclear as to which method of fusion has superior

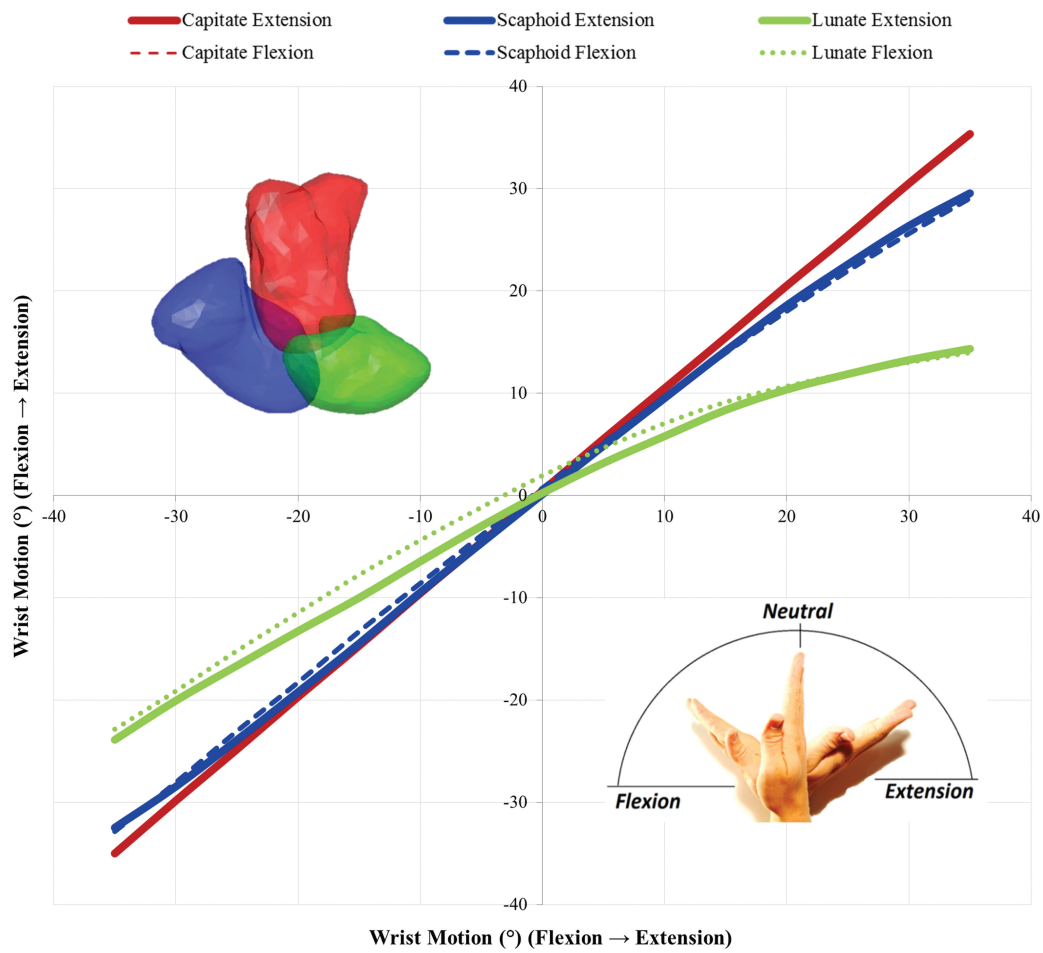

Fig. 5 The mean rotation of the scaphoid and lunate compared with wrist rotation for both flexion and extension trials.

biomechanical potential optimizing wrist motion. Our results provide a better representation of potential outcomes of partial wrist fusions with respect to wrist motion. When performing a midcarpal fusion, the lunate should be fixed in a slightly flexed position allowing for functional wrist extension. Similarly, when performing a radioscapholunate fusion, the lunate should be fixed in a slightly extended position allowing for functional wrist extension.

Our study has limitations. In addition to only analyzing wrist motion from ± 35 degrees of wrist flexion/extension, motion testing was performed in one anatomic plane to maintain reproducibility, not incorporating the complex multiplanar motions of the wrist. Carpal kinematics were considered in one anatomic plane, not considering the rotational and translational movements of the bones throughout flexion/extension. Additionally, motion was performed passively, and any potential soft-tissue adaptation was neglected. However, balanced tendon loading was applied across the wrist to mimic physiologically relevant forces that may occur clinically with active motion. Future work will investigate the effect of dynamic stabilizers and varied tone loads on carpal kinematics. Our study deviated from the ISB-suggested volumetric centroid coordinate system, although we only reported joint angles that would be unaffected by origin definition. Our study has several strengths. This study uses a highly accurate optical motion capture system facilitating real-time kinematic measurements. Additionally, this study analyzed normal kinematics of the native wrist in the flexion/extension plane throughout continuous motion compared with interpolating static positions, which may neither effectively represent dynamic motion nor recreate normal kinematics.[23]

Overall, our findings support a relative collaboration of the scaphoid, lunate, and capitate during wrist flexion/extension. We found that the scaphoid and lunate rotated more during wrist flexion compared with extension, suggesting that the radiocarpal joint has a greater influence during flexion and the midcarpal joint is more important for extension. The large magnitude of differential rotation observed between the scaphoid and lunate may explain, in part, the high incidence of scapholunate ligament injuries relative to other intercarpal ligaments. A detailed understanding of normal and abnormal carpal kinematics may assist in the future design and development of wrist arthroplasty, assist surgeons in positioning the carpal bones when performing partial wrist fusions, and help develop better techniques for scapholunate ligament repair and reconstruction.

Note

All work was performed at the Hand and Upper Limb Clinic in London, Ontario.

Conflict of Interest
None.

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