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Simulated Radioscapholunate Fusion Alters Carpal Kinematics While Preserving Dart-Thrower's Motion

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Abstract

Purpose—Midcarpal degeneration is well documented after radioscapholunate fusion. This study tested the hypothesis that radioscapholunate fusion alters the kinematic behavior of the remaining lunotriquetral and midcarpal joints, with specific focus on the dart-thrower's motion.

Methods—Simulated radioscapholunate fusions were performed on 6 cadaveric wrists in an anatomically neutral posture. Two 0.060-in. carbon fiber pins were placed from proximal to distal across the radiolunate and radioscaphoid joints, respectively. The wrists were passively positioned in a custom jig toward a full range of motion along the orthogonal axes as well as oblique motions, with additional intermediate positions along the dart-thrower's path. Using a computed tomography–based markerless bone registration technique, each carpal bone's three-dimensional rotation was defined as a function of wrist flexion/extension from the pinned neutral position. Kinematic data was analyzed against data collected on the same wrist prior to fixation using hierarchical linear regression analysis and paired Student's *t*-tests.

Results—After simulated fusion, wrist motion was restricted to an average flexion-extension arc of 48°, reduced from 77°, and radial-ulnar deviation arc of 19°, reduced from 33°. The remaining motion was maximally preserved along the dart-thrower's path from radial-extension toward ulnar-flexion. The simulated fusion significantly increased rotation through the scaphotrapezium joint, scaphocapitate joint, triquetrum-hamate joint, and lunotriquetral joint. For example, in the pinned wrist, the rotation of the hamate relative to the triquetrum increased 85%. Therefore, during every 10° of total wrist motion, the hamate rotated an average of nearly 8° relative to the triquetrum after pinning versus 4° in the normal state.

Conclusions—Simulated radioscapholunate fusion altered midcarpal and lunotriquetral kinematics. The increased rotations across these remaining joints provide one potential explanation for midcarpal degeneration after radioscapholunate fusion. Additionally, this fusion model confirms the dart-thrower's hypothesis, as wrist motion after simulated radioscapholunate fusion was primarily preserved from radial-extension toward ulnar-flexion.

Keywords

Cadaver; fusion; lunate; radius; scaphoid

Degeneration of the radiocarpal joints is the end result of interrelated traumatic, inflammatory, and metabolic processes. Intra-articular distal radius fractures, perilunate

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dislocations, scaphoid nonunions, chronic scapholunate ligament tears, and avascular necrosis of the lunate may all produce accelerated arthritic changes between the radius and carpal bones. Radioscapholunate (RSL) fusion is one surgical treatment for such degeneration. The goal of this limited wrist arthrodesis is to provide pain relief while preserving some wrist motion. Radioscapholunate fusion is an important option when the distal radius articular surface is degenerative, which would traditionally preclude proximal row carpectomy.

Nevertheless, RSL fusion is not without complication. Notably, published clinical outcomes after RSL fusion report midcarpal arthritis in up to 50% of these patients.¹⁻⁴ This will become symptomatic in some patients and may even require conversion to a total wrist arthrodesis. Likely multifactorial in nature, the etiology of this midcarpal degeneration has not been established. Proposed theories explain the degeneration as a delayed effect of the initial insult or as an effect of altered joint environments resulting from the fusion. We postulate that RSL fusion alters the remaining carpal joint mechanics, which contributes to early articular degeneration, and that this effect is detectable as kinematic changes.

Recent *in vivo* investigations in our laboratory have examined the kinematics of the radiocarpal joints and the dart-thrower's motion.⁵ This work identified and confirmed findings from Ishikawa et al and Werner et al that the oblique plane of wrist motion from radial extension toward ulnar flexion uniquely involved minimal scaphoid and lunate rotation.⁵⁻⁷ Wrist motion along this dart-thrower's path has been postulated to represent an important functional plane of motion. The high stability of the scaphoid and lunate during this motion suggests that the dart-thrower's motion could be selectively preserved after fusion of the radioscaphoid and radiolunate articulations.

To date, the kinematic behavior of the midcarpal and lunotriquetral articulations after RSL fusion has not been quantified. Furthermore, none of the existing literature on RSL fusions has examined postoperative motion in any oblique plane.^{1,2,3,4,8} Therefore, this cadaveric study of simulated RSL fusions was designed to define the immediate kinematic consequences of this limited wrist arthrodesis. To do this, we evaluated carpal bone motion in cadaver wrists before and after simulated RSL fusion. We tested the hypotheses that (1) midcarpal kinematics would be altered by the simulated fusion and (2) that the dart-thrower's motion would be selectively preserved after RSL fusion.

Materials and Methods

Six fresh-frozen cadaver arms were used for this study. This group consisted of upper extremities from 3 men and 3 women averaging 68 years of age (range, 51–80 years). No specimen had visual or radiographic evidence of preexisting carpal arthritis or malalignment. All wrists were thawed to room temperature overnight in advance of testing.

The extremities were positioned in a custom-designed jig such that the humerus was vertical with the elbow flexed at 90° and the forearm in neutral pronosupination. The ulna was secured to the jig with a rigid bar through the interosseous membrane to minimize any shifts in forearm position during scanning. The hands were placed in a resting grip position around handles transfixed with polymer screws through the second and fourth metacarpals. The wrist flexor (flexor carpi radialis, flexor carpi ulnaris) and the wrist extensor (extensor carpi radialis brevis, extensor carpi radialis longus, extensor carpi ulnaris) tendons were each captured with running suture proximal to the wrist. The suture ends were then looped together creating composite flexor and extensor groups. The suture coursed parallel with the forearm over pulleys on the posterior edge of the jig where 0.45 kg (1.0 lb) of weight was

attached to tension the flexor and extensor groups, respectively. This was designed to reproduce resting muscle tension across the carpus.⁹

Wrists were imaged using a 16-slice computed tomography (CT) scanner (General Electric Highspeed Advantage, Milwaukee, WI) at 120 kVp and 80 mA. Volume images consisted of 1.0-mm slices and in-plate resolution of 0.3 mm × 0.3 mm for the neutral position and 0.9 mm × 0.9 mm for all other postures.

Wrist position during scanning was assessed visually with the aid of orthogonal protractors on the cadaver jig that defined flexion/extension and radial/ulnar deviation. Scanning commenced with the wrists in the anatomically neutral position, defined as the dorsum of the third metacarpal parallel to the dorsal surface of the forearm, in both the sagittal and coronal planes. After the neutral scan, wrists were passively positioned through a range of motion guided by protractors on the jig. Target positions included a standard full range of motion protocol: 40° of flexion (40F), 40° of extension (40E), 10° of radial deviation (10R), 30° of ulnar deviation (30U), and combined positions of ulnar flexion (40F/30U), ulnar extension (40E/30U), radial extension (40E/10R), and radial flexion (40F/10R), as well as 4 additional positions along the dart-throwers path (2 combined positions of ulnar flexion [10F/10U and 30F/20U] and 2 of radial extension [10E/10R and 20E/20R]).

After this initial scanning, the 6 cadaver wrists underwent simulated RSL fusion. Each of the wrists was fixed in an anatomically neutral position using 1.6 mm (0.062 in.) K-wires placed under fluoroscopic guidance. Two diverging wires were inserted into the lunate and scaphoid respectively from the distal radius directed from proximal to distal (Fig. 1). The fixation was placed to immobilize the lunate and scaphoid in neutral position without any appreciable coronal or sagittal deviation. Care was taken to ensure the K-wires did not penetrate the midcarpal joint. The wire depths were measured and the wires were replaced with 0.060-in. radiolucent carbon fiber pins to prevent metallic interference during subsequent CT scanning. Wrists were moved through a range of motion at the completion of pin placement under live fluoroscopy to grossly verify effective fixation of the scaphoid and lunate to the radius. No violation of the radiocarpal ligaments or joint capsule occurred during this fixation.

Once the simulated RSL fusions were completed, the wrists were CT scanned again using the same jig and scanning protocol described above. The only change in protocol occurred due to the restricted wrist motion after the simulated fusion. If motion of the wrist toward the targeted position was limited by the fixation, the wrist was positioned only as permitted passively without resistance. Therefore, wrists were passively positioned at the limits of a resistance-free arc at which point they were secured in the jig.

Kinematic analysis was performed using a markerless bone registration technique previously described.¹⁰ Bony surfaces were generated from the high-resolution neutral-position CT scans using Analyze (Biomedical Imaging Resource, Mayo Foundation, Rochester, MN), Geomagic Studio (Raindrop Geomagic, Research Triangle Park, NC), and custom code written using MATLAB (The Mathworks, Natick, MA) and C++. For analysis purposes, all left wrists were converted to right wrists, and each carpal bone was aligned to its neutral position using tissue-classified distance fields.¹¹ For all of the non-neutral postures, the radius was registered to the neutral position for each respective series in order to eliminate confounding motion produced by any shifts in the forearm position during the scanning protocol. Three-dimensional carpal kinematics were described using helical axes of motion (HAM) variables in an anatomic-based coordinate system defined by the radius.¹² Final wrist position for analysis was defined by the computed capitate position relative to the distal radius, as this has been proved more accurate than external references.¹³

Motions of the scaphoid and lunate were described relative to the radius. To measure motion at the scaphotrapezium, scaphocapitate, triquetrohamate, and lunotriquetral joints, the kinematics were described as trapezium relative to the scaphoid, capitate relative to the scaphoid, hamate relative to the triquetrum, and triquetrum relative to the lunate, respectively.

To determine if the carpal bones rotated about the same axis before and after pinning, we compared the orientation and location of the resultant HAM axes during flexion and extension of the capitate (relative to the scaphoid). Wrist positions were filtered to exclude those with more than 10° of radial or ulnar deviation or a total rotation of less than 5° because of the noise associated with computing axis location and orientation for small angles. The locations of the HAM axes in the pinned wrists were corrected for any translation of the capitate in the x direction that resulted from pinning. The translation of the capitate in the x direction, between the unpinned neutral wrist and the pinned neutral wrist, was subtracted from the location of the HAM axes for the remaining non-neutral postures in the pinned wrist. The orientations and locations of the axes were then averaged to create a single HAM axis for the pinned wrists and for the unpinned wrists.

Kinematic data for the fused wrists was compared with data collected on the same wrist prior to simulated fusion. Outcome variables included the global wrist motion before and after fixation, as well as the kinematics at the radioscaphoid, radiolunate, scaphotrapezium-trapezoid, scaphocapitate, triquetrohamate, and lunotriquetral joints. Three-dimensional rotations were therefore defined for the scaphoid and lunate relative to the radius, trapezium relative to the scaphoid, capitate relative to the scaphoid, hamate relative to the triquetrum, and triquetrum relative to the lunate. Hierarchical linear regression analysis and paired Student's *t*-tests were used to statistically assess the impact of the simulated fusion on each of these variables. We used statistical software Sigma Stat and Sigma Plot (Systat Software Inc., San Jose, CA) to perform these tests.

Results

In this study, a total of 13 wrist positions were targeted for both the unpinned and pinned cadaver wrists. Of the 78 unpinned CT series and 78 pinned CT series, 154 series were acquired and analyzed with only 2 (1 position for each of 2 pinned wrists) dropped because of output errors from the CT scanner.

Performing the simulated fusion resulted in small changes in carpal position. After pin fixation, the scaphoid was pushed distally on average 1.9 mm (range, 0.3 mm proximal to 3.6 mm distal), and the lunate moved an average of 1.3 mm distally (range, 0.2 mm to 3.1 mm distal). The simulated fusion caused both bones to rotate in flexion/extension and radial/ulnar deviation. The average rotational change in posture due to pinning, regardless of direction, was 9° (SD 6°) for the scaphoid and 8° (SD 3°) for the lunate.

The average HAM axes representing flexion/extension rotations of the capitate relative to the scaphoid for the pinned and unpinned wrists were oriented within 2° of one another (Fig. 2). The 2 average HAM axes were located less than 1 mm apart.

The fixation of the lunate and scaphoid did not provide absolute stability. After pinning, the scaphoid and lunate rotated an average of 4° and 2° across all positions, relative to their pinned neutral position.

After simulated fusion, global wrist motion markedly decreased. The mean fused flexion-extension arc was 48° (range, 44° to 53°) down from 77° before pinning, with a mean radial-ulnar deviation arc of 19° (range, 14° to 27°) down from 33°. Total wrist motion

after pinning was maximally preserved along the dart-thrower's path directed from ulnar flexion toward radial extension (Fig. 3).

The three-dimensional rotation of the scaphotrapezium, scaphocapitate, triquetrohamate, and lunotriquetral joints significantly increased ($p < .01$) after the simulated fusion. These rotations were described as relative motion between the two articulating carpal bones as a function of wrist flexion and extension. Table 1 presents the mean slopes of the best fit lines describing the relative rotations occurring through the specified joints in each extremity before and after simulated fusion. After simulated fusion, the rotation of the hamate relative to the triquetrum increased 85% (Fig. 4). Therefore, during every 10° of total wrist motion, the hamate rotated an average of nearly 8° relative to the triquetrum after pinning versus 4° in the normal state. Across the remaining midcarpal articulations, postfusion changes were of even greater magnitude. The simulated fusion increased capitate rotation relative to the scaphoid by 275% (Fig. 5). In the scaphotrapezio-trapezoidal joint, trapezium rotation relative to the scaphoid after fixation was 4.5 times that in the unpinned state (Fig. 6). Kinematic data after simulated fusion demonstrated minimal detectable rotation of the trapezoid relative to the trapezium. Therefore, only the trapezium's rotation relative to the scaphoid was analyzed.

The simulated RSL fusion also increased the rotation of the triquetrum relative to the lunate. The resultant 200% increase in rotation across the remaining proximal row joint represented an additional 3° of motion (4° vs 1°) for every 10° of total wrist motion (Fig. 7).

Discussion

Radioscapholunate fusion represents a viable surgical solution to persistently symptomatic radiocarpal degeneration. However, RSL fusion is associated with an increased incidence of midcarpal degeneration and pain. Given this documented degeneration in surrounding articulations after the fusion, we hypothesize that this is due to altered kinematics and joint loading after fusion. Accordingly, this study was performed to evaluate the change in midcarpal and lunotriquetral kinematics after RSL fusion. To do so, we studied kinematics in cadaver wrists before and after a simulated fusion. We found that this simulated fusion reduces overall wrist range of motion, increases midcarpal motion, and has minimal effect on motion along the dart-thrower's path.

The wrist motion preserved after our simulated fusions fell within the range of that found in published clinical series of RSL fusions (Table 2). We believe that this supports the fact that this model is producing effects similar to true fusions. The 2 largest clinical series also note that the exact posture of the fused lunate (8° flexed to 25° extended) did not affect the amount of postoperative motion.^{1,4} This observation suggests that the small changes in lunate posture noted after simulated fusion should not have negatively affected our results. In our study, the lunate's posture in the pinned specimens averaged within 8° of the neutral posture of the unpinned lunate. The scaphoid's posture in the pinned specimens was within 10° of the neutral posture of the unpinned scaphoid. The direction of these changes in posture varied between specimens and ranged from 16° extended to 14° flexed for the scaphoid and from 10° extended to 12° flexed for the lunate.

To our knowledge, this cadaver model is the first attempt to describe the specific kinematic effects of RSL fusion. In this study, changes in kinematic patterns across the midcarpal and lunotriquetral joints were found. These changes occurred at the time of the fixation and would likely persist over time. Clinically, whereas midcarpal arthritis is known to develop after RSL fusion, the etiology of this degeneration is unknown. Potentially, this arthritis could result from the initial injury (or condition) necessitating the fusion or could represent a

sequela of the fusion itself. Patients experiencing perilunate dislocations and severe distal radius fractures may have sustained cartilaginous damage to the midcarpal joints at the time of injury. Similarly, the patient with chronic scapholunate ligament disruption, scaphoid nonunion, or Kienbock's disease may have early degeneration in the midcarpal articulations at the time of surgery. The radiographic evidence of such midcarpal damage in this patient population may progress slowly and become evident on radiographs only after the fusion is performed. Conversely, the orthopedic literature documents degeneration in presumably normal joints adjacent to fusions.^{14–16} In these cases, it is hypothesized that the loss of motion at the fusion site affects the mechanical environment of adjacent joints as they are forced to compensate for the lost motion. Changes in the kinematics of the surrounding carpal articulations in this study are believed to represent a quantifiable measure of this altered environment. Provided the immediate, significant effects on each of the remaining carpal joints, it is plausible that the midcarpal degeneration after RSL fusion may in part represent an effect of the fusion. However, research providing longitudinal data in an *in vivo* model would be required to further substantiate this theory.

As in any limited fusion of the wrist, the goal of RSL fusions is to provide pain relief while preserving wrist motion. Ideally, the remaining motion represents functional movement that allows one to accomplish the activities of daily living. Classic studies designed to define functional wrist motion have focused on motion along the orthogonal planes of flexion/extension and radial/ulnar deviation.^{17–19} However, oblique motion along the dart-thrower's arc from radial-extension toward ulnar-flexion has been proposed to represent an especially important functional plane of motion.^{5,20,21} During testing, it was evident that whereas the purely coronal and sagittal wrist motion was markedly reduced after simulated RSL fusions, oblique motion along the dart-thrower's arc was preferentially preserved. This finding was expected given previous investigators consistently reporting that this arc uniquely involves minimal scaphoid and lunate motion.^{5,6,7,20,22} As all previous outcomes studies after RSL fusions have only reported postoperative motion measured in the traditional orthogonal planes, it is possible that these measurements underestimate the remaining functional capacity of these wrists.^{1,3,4,8,23}

We were not able to detect a change in the orientation and location of the HAM axes of the capitate for flexion/extension after pinning. However, due to the high degree of variability within the individual HAM axes associated with each position, it is premature to say that direction of motion is not altered during RSL fusion. These results are consistent with the anatomy of capitate and its proximal joint seated in the scaphoid and lunate.

There are several limitations inherent in this cadaver study. The validity of our results relies upon the assumption that the carpal ligaments guiding wrist motion *in vitro* behave similar to those *in vivo*. However, we presume these differences to be small, as these cadavers were analyzed through a full wrist range of motion prior to simulated fusion and found to closely replicate *in vivo* data (Moore et al, presented at the Transaction of Orthopedic Research Society, March 19–22, 2006, Chicago, IL). In an effort to maximize our ability to accurately interpret the CT scanned data, carbon pins were used for the simulated fusions. Although subjectively comparable in bending rigidity to similarly sized K-wires, these rods did not provide for completely rigid fixation of the scaphoid and lunate to the radius. In this cadaver model, external fixation or screw fixation would have provided absolute stability for this fusion model. Rigid fixation was not used as it would have required drilling larger holes in the bony cortices and created marked radiographic artifact both of which would have compromised our ability to produce accurate kinematic data. In view of a lack of completely stable scaphoid and lunate fixation, our results likely overestimate total wrist motion slightly, especially in the anti– dart-thrower's path, while underestimating the kinematic alterations at the individual remaining carpal articulations. Additionally, the changes in

carpal kinematic behavior only represent effects immediately after the fixation. After true RSL fusions, time-dependent changes produced by ligament stresses or potential arthritic changes at remaining carpal articulations are expected and are not reproduced in this experimentation. Finally, this testing protocol did not include excision of the distal scaphoid as may be performed in conjunction with RSL fusion. A recent series by Garcia-Elias et al has supported distal scaphoid excision, and Hastings has reported excising the triquetrum during RSL fusion.^{23,24} Excision of the distal pole of the scaphoid would have likely led to a greater arc of wrist motion; however, the distal scaphoid was not excised in this experiment for 2 reasons. First, we aimed to evaluate the kinematic effects of this fusion without violating the wrist capsule and without surgically disrupting the wrist ligaments in an effort to minimize the chance of producing kinematic alterations during fixation. Second, the clinical literature regarding RSL fusion, to which we compared our results, has not included distal scaphoid excision.¹⁻⁴

Conclusions made from the data presented regarding the percentage of total wrist motion sacrificed in this simulated fusion model must be qualified. A previously published cadaver study of RSL fusions reported only the percentage of wrist motion lost after fusion.²⁵ Although our simulated fusions appeared to have sacrificed less motion (38% vs 64% of flexion/extension; 41% vs 53% reduction in radioulnar deviation) and minimally reduced motion along the targeted dart-thrower's positions (50° down to 43°), it is likely that this is confounded by our experimental methods. Namely, whereas the pinned wrists reached their extremes of motion during imaging, the unpinned wrists were positioned in all directions but not formally stressed to maximize each direction's motion. The unpinned wrists were not imaged in extreme positions as the original goal of the investigation was not to quantify the absolute reduction in total wrist motion after pinning. Instead, we aimed to collect kinematic data in a manner consistent with our prior *in vivo* protocols to allow for validation of our model and reliable comparison between the unpinned and pinned states. Therefore, whereas the absolute values of motion after fusion are believed accurate, it is likely that our results overestimate the percentage of preserved wrist motion from the natural state. Despite its limitations, this study demonstrated convincingly that midcarpal and lunotriquetral motion is increased after simulated RSL fusion. Furthermore, although global wrist motion was markedly restricted, postoperative motion is selectively preserved along the dart-thrower's path.

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Figure 1.
A Posteroanterior and **B** lateral fluoroscopic images of wrist during simulated RSL fusion.

Figure 2.
Capitate Helical Axis of Motion (HAM) before and after simulated RSL fusion.

Figure 3.

Plot of wrist positions demonstrating limited motion after simulated RSL fusion with the greatest preserved arc from radial-extension toward ulnar-flexion.

Figure 4.

Rotation of hamate relative to triquetrum. Best fit lines demonstrate greater rotation of the hamate relative to the triquetrum after simulated fusion. Note: Figures of individual carpal rotations present composite best fit lines for all specimens in normal and fused conditions used for illustration but not for data analysis.

Figure 5.

Rotation of capitate relative to scaphoid. Best fit lines demonstrate greater rotation of the capitate relative to the scaphoid after simulated fusion.

Figure 6.

Rotation of trapezium relative to scaphoid. Best fit lines demonstrate greater rotation of the trapezium relative to the scaphoid after simulated fusion.

Figure 7. Rotation of triquetrum relative to lunate. Best fit lines demonstrate greater rotation of the triquetrum relative to the lunate after simulated fusion.

Table 1
Mean Slopes of Best Fit Lines of the 3-Dimensional Rotation Across the Scaphotrapezial, Scaphocapitate, Triquetrohamate, and Lunotriquetral Joints Before and After Simulated Fusion

Joint	Mean Slopes ($\pm$ SD), Unpinned	Mean RMSE ($^{\circ}$)	Mean Slopes ($\pm$ SD), Simulated Fusion	Mean RMSE ($^{\circ}$)
Triquetrohamate	0.41 ($\pm$ 0.08)	5.9	0.76 ($\pm$ 0.05)*	2.9
Scaphocapitate	0.24 ($\pm$ 0.06)	8.2	0.90 ($\pm$ 0.17)*	3.8
Scaphotrapezial	0.19 ($\pm$ 0.03)	10.2	0.86 ($\pm$ 0.20)*	4.6
Lunotriquetral	0.12 ($\pm$ 0.04)	3.6	0.36 ($\pm$ 0.12)*	3.0

RMSE, root mean square error.

* Significant to $p < .01$.

Table 2
Comparison of Mean Postoperative Motions in This Cadaver Model Versus Those
Reported in RSL Clinical Studies*

	Flexion-Extension Arc (°)	Radial-Ulnar Deviation Arc (°)
RSL literature*	49.6 (range, 26 to 70)	23.9 (range, 5 to 47)
Current study	47.9 (range, 44 to 53)	19.3 (range, 14 to 27)

* Sources: Nagy and Buchler,¹ Bach et al,⁴ and Watson et al,⁸ with total 26 patients.