Biomechanics of an Articulated Screw in Acute Scapholunate Ligament Disruption

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Abstract

Background An injury to the scapholunate interosseous ligament (SLIL) leads to instability in the scapholunate joint. Temporary fixation is used to protect the ligament during reconstruction or healing of the repair. Rigid screw fixation—by blocking relative physiological motion between the scaphoid and lunate—can lead to screw loosening, pullout, and fracture.

Purpose This study aims to evaluate changes in scaphoid and lunate kinematics following SLIL injury and the effectiveness of an articulating screw at restoring preinjury motion.

Materials and Methods The kinematics of the scaphoid and lunate were measured in 10 cadaver wrists through three motions driven by a motion simulator. The specimens were tested intact, immediately following SLIL injury, after subsequent cycling, and after fixation with a screw.

Results Significant changes in scaphoid and lunate motion occurred following SLIL injury. Postinjury cycling increased motion changes in flexion-extension and radial-ulnar deviation. The motion was not significantly different from the intact scapholunate joint after placement of the articulating screw.

Conclusion In agreement with other studies, sectioning of the SLIL led to significant kinematic changes of the scaphoid and lunate in all motions tested. Compared with intact scapholunate joint, no significant difference in kinematics was found after placement of the screw indicating a correction of some of the changes produced by SLIL transection. These findings suggest that the articulating screw may be effective for protecting a SLIL repair while allowing the physiological rotation to occur between the scaphoid and lunate.

Clinical Relevance A less rigid construct, such as the articulating screw, may allow earlier wrist rehabilitation with less screw pullout or failure.

Keywords

- ▶ scapholunate interosseous ligament injury
- ▶ scaphoid and lunate kinematics
- ▶ screw fixation
- ▶ flexion-extension
- ▶ radial-ulnar deviation
- ▶ dart-thrower's motion
- ▶ biomechanics

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Injury to the scapholunate (SL) joint is a commonly encountered injury with clinically significant sequelae. The SL articulation is stabilized by multiple carpal ligaments, with the most important stabilizer being the SL interosseous ligament (SLIL).^{1,2} Injury to the SLIL leads to instability of the SL joint. Previous studies have shown altered scaphoid and lunate kinematics following SLIL sectioning, with the tendency of the scaphoid to flex volarly and the lunate to extend dorsally.^{1,3,4} It is believed that this kinematic alteration causes pathological loading and articulation of the carpal bones, leading to a spectrum of degenerative changes and functional impairment.^{5,6}

Several SLIL repair and reconstruction options are available including direct repair,^{7,8} capsulodesis,^{8,9} tendon grafting,¹⁰ bone-tissue-bone reconstruction,^{11,12} and ligament tenodesis.^{13,14} To protect the repair, temporary fixation of the SL joint is performed to restrict intercarpal motion and prevent disruption or stretching of the repair during the healing process. While most surgeons utilize Kirschner wires for this fixation,¹⁵ screw fixation across the SL joint may provide a stronger and more durable alternative.¹⁶

Due to the rigidity of screw fixation, the physiological movement and relationship of the scaphoid and lunate is disrupted eventually leading to screw loosening, pullout, and fracture.¹⁶⁻²¹ Reporting his results utilizing screw fixation in SL ligament injuries, Herbert recognized that the ideal implant should be strong enough to protect the SL repair, but "flexible enough to allow the normal motion to occur at the scapholunate joint."¹⁹

A newly designed screw (Acumed, Portland, OR) features a headless, cylinder-in-cylinder design with a joint in the central portion of the screw. This joint permits motion between the two components of the screw with full relative rotation along the long axis of the screw and 15 to 22 degrees of toggle perpendicular to this long axis. Theoretically, when placed across the SL joint, the screw prevents SL diastasis in the same way as screw fixation, while allowing independent scaphoid and lunate rotation in the sagittal plane of the wrist.

Regardless of the technique selected, the goal of SL ligament repair is to restore the normal relationship of the scaphoid and lunate.²²⁻²⁴ While several studies have demonstrated abnormal kinematics of the scaphoid and lunate following SLIL sectioning,^{1,3,25,26} the biomechanics of the SL joint after repair has yet to be clarified.

The purpose of this study was to evaluate the changes in the kinematics of the scaphoid and lunate following SLIL disruption, as well as to determine the effectiveness of the articulating intercarpal screw at restoring preinjury kinematics in a cadaver model.

Materials and Methods

We studied 10 fresh frozen cadaver arms from young adult males (age: 29–44 years). Fluoroscopic evaluation and examination of each wrist was performed to rule out preexisting osteoarthritis or static wrist instability (Orthoscan Mobile DI, Orthoscan Inc., Scottsdale, AZ).

All specimens were prepared by a single surgeon to minimize variation in technique. First, the radius and the ulna were fixed using two Steinmann pins in neutral forearm rotation.²⁷ Next, the forearm was dissected, removing skin and subcutaneous tissue to the metacarpophalangeal joint dorsally and the distal wrist crease on the volar side. Once the skin was removed, moist gauze was used to prevent desiccation.

The tendons of the abductor pollicis longus, extensor carpi radialis longus and brevis, extensor carpi ulnaris, flexor carpi ulnaris, and flexor carpi radialis were dissected and separated at the musculotendinous junction. A running, locking Krakow stitch was placed in each tendon using 2-0 braided suture. Threaded Steinmann pins were fixed across the metacarpophalangeal joints into the index, middle, and ring finger metacarpals for attachment of the hand to the motion simulator.

Under fluoroscopic guidance, 0.062 inch (1.6 mm) threaded Kirschner wires were placed in the third metacarpal at the proximal metaphysis, in the distal radius just proximal to the Lister tubercle, in the waist of the scaphoid, and in the lunate. The lunate wire was placed in the distal and ulnar corner to avoid the path of the SL fixation screw. Infrared emitting targets (as explained below) were later attached to these wires.

The drill hole for the screw was prepared in advance to facilitate placement of the SL screw later in the protocol. A 0.045 inch (1.1 mm) guidewire was placed according to the manufacturer's recommended technique (►Fig. 1). The scaphoid and lunate were then drilled using a cannulated drill until the step of the drill reached the SL interval. Screws were sized but not inserted at this time. The drill and guidewire were then removed.

The wrist was secured to the wrist motion simulator in neutral position²⁷ using the threaded Steinmann pins in the forearm and hand (►Fig. 2). The custom wrist motion simulator was used to generate passive wrist motion using a four-bar linkage, driven by the rotational motion from the actuator of an axial/torsional servohydraulic material testing machine

Fig. 1 Guidewire placement for the scapholunate screw.

Fig. 2 Specimen mounted in the flexion-extension configuration in the wrist motion simulator. The infrared emitting targets (green background) tracked by the motion measurement system, pins in the forearm and hand, and the tendon loading sutures can be seen.

(858 Mini Bionix, MTS, Eden Prairie, MN). The wrist motion simulator was capable of producing any wrist movement from pure wrist flexion-extension, through any specific ratio of radial-extension/ulnar-flexion (i.e., the dart-thrower's motion [DTM]), to pure wrist radial-ulnar deviation.

During testing, the tendons were loaded with weights totaling 100 N divided among the six tendons. The load applied to each tendon was based on studies of the physiological cross-sectional area of forearm musculature.^{27,28} A loaded wrist model was selected based on previous biomechanical studies that demonstrate change in carpal mechanics in loaded and unloaded conditions.^{29,30}

An optoelectronic motion measurement system (Optotrak Certus, Northern Digital, Waterloo, Ontario, Canada) recorded the position and motions of infrared emitting targets, attached to the threaded Kirschner wires in the lunate, scaphoid, distal radius, and third metacarpal (►Fig. 2). A digitizing probe was used to locate the three-dimensional relationship between the target and its connection to the bone. Translation and rotation motions of the targets were then transformed to this position at the juncture of bone and wire.

Motion data were collected for each specimen state (intact, transected SLIL, transected SLIL after 1,000 cycles of flexion-extension (FE), and after screw fixation) during 10 cycles of flexion-extension (FE), radial-ulnar deviation (RUD), and the DTM (►Fig. 3). For FE, the wrist was moved in a sinusoidal motion pattern from 15 degrees of flexion to 15 degrees of extension (►Fig. 2). For RUD, the wrist moved from 10 degrees radial deviation to 10 degrees ulnar deviation. Finally, for DTM, the wrist was positioned in the DTM position, approximately 18 degrees from the sagittal plane to cycle the wrist from radial/extension to ulnar/flexion. The wrist was cycled from 4 degrees radial/12 degrees extension to 4 degrees ulnar/12 degrees flexion. The reported ranges of motion are the minimum global wrist rotations (motion between the third metacarpal and distal radius) measured in the 10 specimens. Wrist joint torques were not monitored or measured. To prevent specimen damage, a conservative range of motion was chosen of at least one standard deviation below the mean

Fig. 3 Flowchart showing the experimental protocol steps. Motion data (during flexion-extension, radial-ulnar deviation, and dart-thrower's motion) was collected for the four different specimen states indicated.

ranges of motion, reported by Crisco et al., for a 2 Nm applied moment.²⁷

The SLIL was transected through a small incision developed in the interval between the dorsal radiocarpal and dorsal intercarpal ligaments.³¹ Under fluoroscopic guidance, a scalpel was advanced proximally and distally until the entire SLIL was released (►Fig. 3).

After 1,000 FE stress cycles, posterior-anterior and lateral fluoroscopic images were obtained to evaluate the SL relationship. No change in SL angle or SL gap was observed. Under fluoroscopic guidance, the guidewire was replaced into the previously drilled hole. To prevent distraction of the joint during screw placement, the SL joint was compressed using a pointed bone reduction clamp. The appropriately sized screw was then placed over the guidewire and advanced until the junction of the screw was at the SL joint. Fluoroscopic images were obtained to confirm placement (►Fig. 4A). Extended cycling was not performed after screw placement.

Statistical analysis was performed on kinematic motion data from the 10th and last cycle of FE, RUD, and DTM with: (1) the SLIL intact, (2) after transection of the SLIL, (3) after transection of the SLIL and 1,000 FE stress cycles, and (4) after placement of the screw.

All 10 screws were intact at the end of data collection and were removed (►Fig. 4B). A dorsal wrist capsulotomy was made and the SL joint examined to confirm the complete release of the SLIL. The midcarpal and radiocarpal joints were

Fig. 4 (A) Postexperiment X-ray radiograph showing the placement of the scapholunate screw. (B) Photograph of the retrieved articulating scapholunate screw.

also examined, and no specimen was found to have evidence of degenerative changes of the wrist.

Custom programs were used to calculate scaphoid, lunate, third metacarpal, and distal radius motion during wrist movement (MATLAB, Mathworks Inc., Natick, MA). Individual movement of the scaphoid and lunate was compared with the global wrist motion (motion between the third metacarpal and distal radius). For each wrist motion (FE, RUD, and DTM), scaphoid flexion/extension, scaphoid radial/ulnar deviation, lunate flexion/extension, lunate radial/ulnar deviation, and SL gapping was calculated relative to intact SL joint and 0 degrees of motion. SL gap was calculated as coronal plane translation between the two bones. Based on the coordinate axis used in the analysis, flexion and ulnar deviation were positive, and extension and radial deviation were negative.

Analysis of variance was used to compare the position of the scaphoid and lunate with an intact ligament, after cutting the SLIL, after 1,000 cycles of FE, and after placement of the screw at discrete points during FE, RUD, and DTM. A p value of less than 0.05 was considered statistically significant.

Fig. 5 Scaphoid radial-ular deviation during wrist flexion-extension. Radial deviation is negative on the y-axis while ulnar deviation is positive.

Results

Compared with the intact state, transecting the SLIL resulted in significant changes in scaphoid and lunate motion during wrist FE, RUD, and DTM. Cycling the wrist through 1,000 cycles of FE resulted in further statistically significant changes during wrist FE and DTM but not RUD. After placement of the articulating screw across the SL joint, there was no significant difference in scaphoid and lunate motion during wrist FE, RUD, or DTM compared with the intact state ($p > 0.05$). Both SLIL sectioning and additional cycling of the wrist through 1,000 FE cycles did not produce a statistically significant gap between the scaphoid and lunate during FE ($p \geq 0.36$), RUD ($p \geq 0.29$), or DTM ($p \geq 0.52$).

Motion Changes with Wrist Flexion-Extension

During wrist FE, sectioning of the SLIL caused the scaphoid to radially deviate ($p = 0.02$), and cycling of the wrist led to further scaphoid radial deviation ($p = 0.02$) (►Table 1 and ►Fig. 5). Following placement of the articulating screw, there was no significant change in motion compared with the intact wrist ($p > 0.05$), showing correction of the radial deviation seen with SLIL disruption and cycling (►Table 1 and ►Fig. 5).

Also, during wrist FE, sectioning of the SLIL caused the lunate to move into flexion ($p = 0.01$) (►Table 1 and ►Fig. 6A). Following cycling of the wrist, the lunate moved into radial deviation compared with before cycling ($p < 0.01$) (►Fig. 6B). However, following placement of the articulating screw,

Table 1 Changes in motion during wrist flexion-extension

Motion changes with wrist flexion/extension	Change in scaphoid motion	Change in lunate motion
SLIL cut	Scaphoid moves into radial deviation ($p = 0.02$)	Lunate moves into flexion ($p = 0.01$)
SLIL cut + 1,000 cycles of FE	Scaphoid moves into further radial deviation ($p = 0.02$)	Lunate moves into radial deviation ($p < 0.01$)
After screw	No change from intact	No change from intact

Abbreviations: FE, flexion/extension; SLIL, scapholunate interosseous ligament.

Fig. 6 (A) Lunate flexion-extension during wrist flexion-extension. Flexion is positive on the y-axis while the extension is negative. (B) Lunate radial-ulnar deviation during wrist flexion-extension motion.

there was no significant change in motion compared with the intact wrist ($p > 0.05$), showing reversal of both the lunate flexion and radial deviation seen after SLIL disruption and cycling (►Table 1 and ►Fig. 6A, 6B).

Motion Changes with Wrist Radial-Ulnar Deviation

During wrist RUD, sectioning of the SLIL caused the scaphoid to move into ulnar deviation ($p = 0.02$) without further change following cycling of the wrist (►Table 2 and ►Fig. 7). After placement of the articulating screw there was no significant change in scaphoid motion as compared with the intact wrist ($p > 0.05$), showing correction of the ulnar deviation seen with SLIL sectioning (►Table 2 and ►Fig. 7).

Also, during wrist RUD, sectioning of the SLIL caused the lunate to move into extension ($p = 0.01$) without further change following cycling of the wrist (►Table 2 and ►Fig. 8). After placement of the articulating screw, there was no significant change in lunate motion compared with the intact

Fig. 7 Scaphoid radial-ulnar deviation during wrist radial-ulnar deviation. Radial deviation is negative on the y-axis while ulnar deviation is positive.

Fig. 8 Lunate flexion-extension during wrist radial-ulnar deviation. Flexion is positive on the y-axis while the extension is negative.

wrist ($p > 0.05$), showing correction of the extension seen with SLIL sectioning (►Table 2 and ►Fig. 8).

Motion Changes with Wrist Dart-Thrower's Motion

During wrist DTM, sectioning of the SLIL caused the scaphoid to ulnar deviate ($p = 0.03$), and cycling of the wrist led to further scaphoid ulnar deviation ($p = 0.04$) (►Table 3 and ►Fig. 9). Following placement of the articulating screw, there was no significant change in scaphoid motion compared with the intact wrist ($p > 0.05$), showing correction of the ulnar deviation seen with SLIL disruption (►Table 3 and ►Fig. 9).

In addition, during DTM, sectioning of the SLIL caused the lunate to move into extension ($p = 0.04$) and ulnar deviation ($p = 0.02$) and cycling of the wrist led to further ulnar deviation ($p = 0.02$) (►Table 3 and ►Fig. 10). After

Table 2 Changes in motion during wrist radial-ulnar deviation

Motion changes with wrist radial/ulnar deviation	Change in scaphoid motion	Change in lunate motion
SLIL cut	Scaphoid moves into ulnar deviation ($p = 0.02$)	Lunate moves into extension ($p = 0.01$)
SLIL cut + 1,000 cycles of FE	No additional change	No additional change
After screw	No change from intact	No change from intact

Abbreviations: FE, flexion/extension; SLIL, scapholunate interosseous ligament.

Table 3 Changes in motion during wrist dart-thrower's motion

Motion changes with wrist dart-thrower's motion	Change in scaphoid motion	Change in lunate motion
SLIL cut	Scaphoid moves into ulnar deviation ($p = 0.03$)	Lunate moves into extension ($p = 0.04$) and ulnar deviation ($p = 0.02$)
SLIL cut + 1,000 cycles of FE	Scaphoid moves into further ulnar deviation ($p = 0.04$)	Lunate moves into further ulnar deviation ($p = 0.04$)
After screw	No change from intact	No change from intact

Abbreviations: FE, flexion/extension; SLIL, scapholunate interosseous ligament.

Note: Statistically significant motion changes of the scaphoid and lunate observed after sectioning the SLIL, cycling the wrist through 1,000 cycles of FE and placement of articulating screw.

placement of the articulating screw, there was no significant change in lunate motion compared with the intact wrist ($p > 0.05$), showing correction of the extension seen with SLIL sectioning (►Table 3 and ►Fig. 10).

Discussion

The purpose of this study was to evaluate the changes in the kinematics of the scaphoid and lunate following SLIL disruption, as well as to determine the effectiveness of the articulating intercarpal screw at restoring preinjury kinematics following SLIL disruption.

Fig. 9 Scaphoid radial-ulnar deviation during wrist dart-thrower's motion. Radial deviation is negative on the y-axis while ulnar deviation is positive.

Fig. 10 Lunate radial-ulnar deviation during wrist dart-thrower's motion. Radial deviation is negative on the y-axis while ulnar deviation is positive.

In our study, we demonstrated that sectioning of the SLIL led to significant changes in the kinematics of both the scaphoid and lunate in all motions tested. We also found no significant difference in kinematics after placement of the screw compared with before SLIL sectioning. This shows that the screw corrected some of the changes in motion produced by SLIL transection while facilitating independent intercarpal rotation seen with an intact SLIL. These findings suggest that the articulating screw may be as efficient as a rigid screw for protecting a SLIL repair while restoring the physiological relationship of the scaphoid and lunate. With a less rigid construct, in clinical practice, the articulating screw may allow earlier wrist rehabilitation with less screw pullout or failure.

In a biomechanical study, Short et al found similar results with a significant change in SL kinematics following SLIL sectioning.¹⁻³ Their model produced similar changes during wrist RUD and DTM, with the scaphoid moving into ulnar deviation and lunate moving into extension. However, their results differed during wrist FE, with the scaphoid moving into flexion and ulnar deviation and the lunate moving into extension rather than the radial deviation observed in this study.

Some of the differences in test setup between Short et al and this study may explain the variance in results during wrist FE. First, Short et al positioned the cadaver vertically. In this orientation gravity acting on the sensors may alter rotations in the FE plane. In our study, the cadaver was horizontally placed. Short et al also applied varying tendon loads to obtain wrist motion while our testing used a passive wrist motion system. Differences in elbow flexion have been found between active motion by applying tendon loads in joint physiological simulators and passive motion using a kinetic motion simulator.³² This finding may also translate to wrist cadaver studies, highlighting another possible difference in the study protocol. Finally, Short et al used a position feedback control to determine the necessary force on the tendons to achieve a predetermined range of motion while our protocol used a consistent ratio of static force for each tendon. Despite these differences in setup and protocol, there are points of agreement between our results and those of Short et al with SLIL sectioning producing a meaningful difference in SL kinematics.

There are several limitations to our study. Our study has a small sample size and no comparison group. Also, data from

cadaveric testing may be different from what might be measured in vivo. Our motion simulator created passive wrist motion while keeping the wrist flexors and extensors statically loaded. Although other authors have used this model,^{33,34} such motion is likely different from normal physiological motion. Other studies have utilized controlled tension on the wrist flexor and extensor tendons to move the wrist actively,^{1,3,31} but these may be more difficult to control and generate less smooth motion.³⁵ Also, while we attempted to minimize the manipulation of the scaphoid, lunate, and surrounding ligamentous structures, the placement of the threaded wires through the dorsal capsule, predrilling the SL joint for the screw before testing and the portal made in the dorsal capsule to cut the SLIL, may have partially disrupted the dorsal radiocarpal ligament and interfered with normal carpal motion. Other authors have utilized the dorsal portal and found that the integrity of the dorsal radiocarpal ligament was not violated with this maneuver.³¹ Finally, using a bone reduction forceps to compress the SL joint during screw placement may have changed the normal relationship of the scaphoid and lunate and resulted in malreduction of the joint.

We detected statistically significant changes in scaphoid and lunate rotation with ligament sectioning and repetitive cycling, but these changes were often less than one degree. The clinical significance of such small changes in motion is not known. Also, our model was unable to create a statistically significant gap between the scaphoid and lunate after cutting the SLIL. Alterations to our protocol, including the addition of greater tendon loads, larger motions arcs for FE, RUD, or DTM, or sectioning the secondary stabilizers of the SL joint, may have generated more significant SL motion abnormalities and gapping. Despite these limitations, use of a motion simulator has value in studying the effects of specific ligament injuries on carpal mechanics. Further research is necessary to expand our understanding of carpal instability and ligament reconstruction.³⁶

In this study, we found significant changes in the kinematics of both the scaphoid and lunate in all motions tested after sectioning of the SLIL in relatively young cadaveric specimens. These kinematic changes were ameliorated by fixation with an articulating intercarpal screw. Our findings suggest that augmenting an acute SLIL repair with the articulating intercarpal screw may be an effective alternative to a rigid compression screw, with potential for less screw fracture and pull out.

Note

This study was performed at the Edward Hines Jr. VA Hospital and was approved by the R&D Committee of Edward Hines Jr. VA Hospital. No ethical review committee approval was required. This work was supported with resources and the use of facilities at the Edward Hines Jr. VA Hospital. The contents do not represent the views of the U.S. Department of Veterans Affairs or the United States Government.

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Conflict of Interest

Dr. Bindra is a consultant for Acumed LLC and Integra LifeSciences (Plainsboro, NJ).

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