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Original Research

Motion and Strength Analysis of 2-Tine Staple and K-Wire Fixation in Scapholunate Ligament Stabilization in a Cadaver Model

Daniel Hess, MD, [*] Anthony Archual, MD, [*] Zachary Burnett, MD, [*] Hans Prakash, BS, [†] Emily Dooley, BS, [‡] Shawn Russell, PhD, [‡] Aaron Freilich, MD, [*] A. Rashard Dacus, MD [*]

[*] Department of Orthopaedic Surgery, University of Virginia, Charlottesville, VA
[†] School of Medicine, University of Virginia, Charlottesville, VA
[‡] University of Virginia Motion Analysis and Motor Performance Lab, Charlottesville, VA

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Purpose: Previous studies have demonstrated the benefits of 2- and 4-tine staple fixation in scapholunate interosseous ligament (SLIL) reconstruction, including improved rotational control and avoidance of the articular surface. This study compared scaphoid and lunate kinematics after SLIL fixation with traditional Kirschner wire (K-wire) fixation or 2-tine staple fixation.
Methods: Eight fresh frozen cadaver arms with normal scapholunate (SL) intervals were included. Infrared motion capture was used to assess kinematics between the scaphoid and lunate as the wrists were moved through a simulated dart-throw motion. Kinematic data were recorded for each wrist in 4 states: SLIL intact, SLIL sectioned, K-wire fixation across SL interval and scaphocapitate joint, and 2-tine Nitinol staple fixation across SL interval. Strength of the SL staple fixation was evaluated using an axial load machine to assess load to failure of the staple construct.
Results: Range of motion of the scaphoid and lunate with SLIL intact and SLIL sectioned were similar. K-wire fixation across the SL interval significantly decreased the overall wrist range of motion as well as scaphoid and lunate motion in all planes except for scaphoid flexion. Conversely, scaphoid and lunate motion after staple fixation was similar to that in normal wrists, except for a significant decrease in scaphoid extension. Under axial load simulating a ground-level fall, 3 of 8 arms demonstrated no failure, and none of the failures was due to direct failure of the 2-tine staple.
Conclusions: This study demonstrates 2-tine staple fixation across the SL interval is effective in providing initial stability and maintaining physiologic motion of the scaphoid and lunate compared with K-wire fixation after SLIL injury.
Clinical relevance: This study demonstrates an alternate technique for the stabilization of the SL interval in repair of acute SLIL injuries using 2-tine staple fixation, which maintains near physiologic motion of the scaphoid and lunate after SLIL injury.

The scapholunate interosseous ligament (SLIL) is important for maintaining normal wrist kinematics, but it is commonly injured during falls or trauma. The SLIL is a C-shaped ligament that functions as the primary ligamentous restraint between the scaphoid and lunate.[1–3] If left untreated, SLIL injury has the potential to lead to the deterioration of wrist function as the secondary stabilizers between the scaphoid and lunate progressively weaken over time because of increased stress placed on them.[4,5] Treatment of SLIL injuries within 6 weeks from the time of injury is preferred because it has been shown to have lower failure rates than treatment of chronic SLIL injuries.[6] However, acute treatment is difficult because SLIL injury is often not immediately recognized, and many patients present only after they develop sequelae from chronic injury.[7,8] Numerous techniques for repair or reconstruction of the SLIL after an acute injury have been described in the literature, but no consensus currently exists regarding optimal treatment.[6,9,10] Each technique has downsides, which may include the need for a second surgery, loss of wrist range of motion, and poor long-term

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Corresponding author: Zachary R. Burnett, MD, University of Virginia, Department of Orthopaedic Surgery, 545 Ray C. Hunt Drive, Charlottesville, VA 22903.

E-mail address: zrb8w@virginia.edu (Z. Burnett).

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outcomes.[6,10] A dart-throw motion, involving movement from radial deviation and wrist extension to ulnar deviation and wrist flexion, has been shown to result in less motion of the proximal carpal row, including the scaphoid and lunate.[11,12] Thus, after a period of immobilization postoperatively, it would likely be one of the first types of motion implemented after repair or reconstruction of the SLIL.[11]

Previous studies have shown some advantages to the use of 2- and 4-tine staples for SLIL reconstruction. In a prior cadaveric study, staples increased rotational stability when used as augmentation to central fixation of the scapholunate (SL) interval.[13] Contrary to Kirschner wire (K-wire) fixation, staples are able to be inserted without the violation of the articular surface. Nitinol is a shape-memory alloy that already has several applications in orthopedic surgery, such as fracture fixation and midfoot arthrodesis procedures after preparation of the joint surfaces.[14,15] Nitinol is composed of varying amounts of nickel and titanium and has been used in the treatment of certain fractures because its pseudoelasticity and shape memory provide inherent compressive properties.[14,16] Nitinol's pseudoelastic property allows it to be 16- to 32-fold more elastic than other alloys.[14] Shape memory permits the alloy to undergo reversible deformation based on temperature. Once placed into bone, the warmer body temperature causes the staple tines to compress to a more rigid, closed position and maintain uniform compression.[17]

Given the potential advantages of staple fixation treatment in SLIL injuries and the successful application of Nitinol staple fixation for other orthopedic procedures, we aimed to investigate the use of Nitinol staple fixation in the treatment of acute SLIL injuries using a cadaver model. The purpose of this study was to compare scaphoid and lunate motion in normal wrists to motion after SLIL fixation using the traditional K-wire fixation technique and 2-tine Nitinol staple fixation. We hypothesized scaphoid and lunate motion with 2-tine staple fixation would more closely resemble that of normal wrists than achieved with K-wire fixation. Additionally, we examined the strength of 2-tine Nitinol staple fixation across the SL interval with an incompetent SLIL, and we hypothesized the staple construct would remain intact at forces simulating a ground-level fall.

Materials and Methods

The methodology used for the hand model in this study was based on protocols described in previously published studies.[3,18,19] Eight fresh frozen cadaver arms were used. A fluoroscopic posteroanterior image of each specimen was taken prior to any dissection to confirm no static diastasis of the SL interval was present. The skin was removed circumferentially to expose the forearm and dorsum of the hand, but the remaining soft tissue structures were left intact. Next, the tendons of the extensor carpi radialis brevis, extensor carpi radialis longus, and flexor carpi ulnaris were isolated. The extensor carpi radialis brevis were attached to each other and a force sensor was affixed dorsally at their proximal extent. The flexor carpi ulnaris was attached to a force sensor volarly at its proximal extent. The radius and ulna were cut distal to the biceps insertion on the radius. The proximal radius and ulna then served as the anchor in a quick-set case mold set in neutral rotation. The scapholunate interval was approached dorsally, as described by Berger et al, creating a capsular/ligamentous flap and sparing the attachments of the dorsal intercarpal and dorsal radiocarpal ligaments.[20] Full release of the dorsal and volar SLIL was performed from this approach, and the scaphoid and lunate were verified to move independently of each other, confirming complete release of the SLIL. This flap was repaired prior to any motion analysis or range of motion trials.

Figure 1. Motion capture setup demonstrating view of wrist with force cells attached to flexor and extensor tendons with overlay of sensors.

Three-dimensional kinematic data were collected using the Vicon Motion Analysis System (Vicon Motion Systems Ltd) and processed via a custom-developed matrix laboratory code. Infrared motion capture was used to assess kinematics between the scaphoid and lunate by analyzing the motion between ridged, mounted 4-marker clusters attached to the scaphoid and a separate cluster attached to the lunate. Similar clusters were also mounted on the long finger metacarpal shaft to serve as an internal reference, and additional clusters were attached to the midshaft of the radius and ulna as well as the base of the box holding the specimen (Fig. 1). Each wrist was moved through 8 cycles of a simulated dart-throw motion from extension and radial deviation to flexion and ulnar deviation by manually pulling through the exposed dorsal extensor carpi radialis brevis/extensor carpi radialis longus at a set force of 30 N to provide extension and radial deviation. For flexion and ulnar deviation, the flexor carpi ulnaris tendon was pulled at a set force of 15 N. Forces were confirmed by single degree of freedom load cells from Interface (Interface Force Measurement Solutions) during the range of motion to keep each motion analysis trial consistent throughout all of the specimens.

The motion of each of the mounted marker clusters was normalized to the ground cluster on the base box. Translations were measured relative to ground and related the insertion point of the cluster to the bone. Rotations were calculated using Tait Bryan angles in the following order: scaphoid and lunate flexion/extension, third metacarpal ulnar deviation, and pronation/supination (relative to the long axis of the forearm). The wrist range of motion was repeated in an identical manner for 8 cycles on each wrist for each of the 4 conditions of interest: SLIL intact, SLIL sectioning, K-wire fixation placed across the SL interval and scaphocapitate joint after SLIL sectioning, and finally 2-tine Nitinol staple placed across the SL interval after SLIL sectioning. For K-wire fixation, 0.062-inch K-wires were placed from the radial aspect of the wrist with 2 K-wires across the scapholunate interval and 1 across the scaphocapitate interval. This is the standard method of K-wire fixation of the SL interval at our institution. Fluoroscopy was used initially to

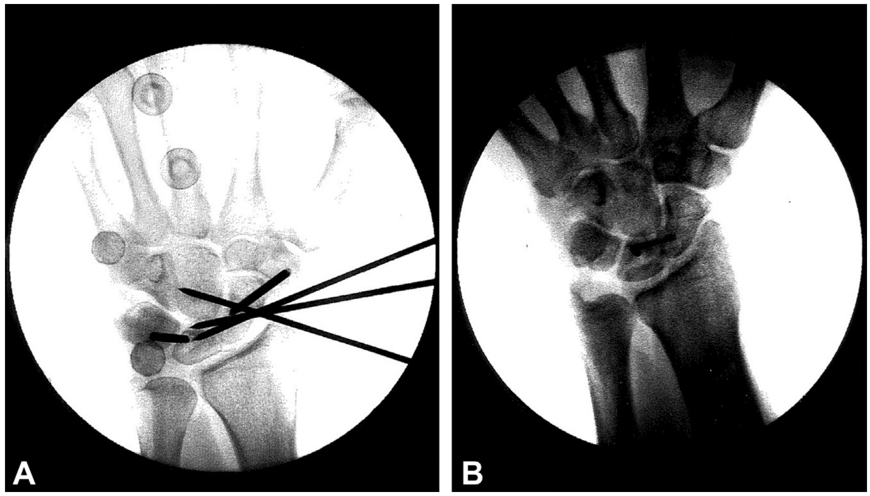

Figure 2. **A** PA x-ray of wrist with K-wire fixation across scapholunate and scaphocapitate interval. **B** PA x-ray with 2-tine staple in place across scapholunate interval.

confirm the proper placement of K-wires and staples and repeated after each motion arc to confirm there was no interval loss of fixation or widening of the SL interval (Fig. 2).

An Integra MemoFix Super Elastic Nitinol staple (Integra LifeSciences) was used. The provided sizing guide was used to determine an appropriate bridge length to span the SL interval, and a 12 mm × 10 mm × 10 mm staple was selected for use in each of the specimens. A 2.0-mm drill bit was used to drill the guide holes in the scaphoid and lunate prior to staple insertion.

Each specimen with the Nitinol staple in place across the SL interval was placed on an MTS Bionic 858 Test System axial load machine (MTS Systems Corp) to evaluate the axial load to failure of the staple. To simulate a catastrophic event such as a fall on an outstretched hand, an axial force was applied to each wrist in full extension at a rate of 100 N/min until the greater of 1000 N or 200% of subject body weight was reached or the failure of staple occurred. Staple failure was defined as the loss of fixation such as staple pull out, staple breakage, or interval widening of the SL interval as determined by direct visualization and fluoroscopy. The maximum force was chosen to simulate the force encountered during a ground-level fall because this would likely be the greatest force that could be anticipated to be encountered in the typical postoperative setting.[21] The point of failure was calculated by assuming that a linear stress-strain relationship with a constant Young's modulus approximated the behavior of the construct. Thus, with a constant increase in force applied by the axial load machine, the compression of the construct should be linearly related to the increase in force. Failure is reached when the second derivative value of the strain curve is no longer zero, indicating the construct is deviating from this linear stress-strain relationship (Fig. 3).

Statistical analysis was performed on the mean value of the dart-throw range of motion for each hand in each of the 4 conditions of interest. The sectioned SLIL, K-wire, and staple conditions were compared with normal range of motion values for each arm using a paired *t* test. Significance was determined to be $P < .05$ for this study. Post-hoc analysis was performed to determine the power of our study to detect a difference in wrist range of motion with staple or K-wire fixation and was found to be 0.985.

Results

The 8 cadaver arms had an average age of 76.3 years (range, 62–89). The mean weight of the cadaver was 160 pounds (range, 100–208). Overall wrist flexion-extension and radial-ulnar deviation through a dart-throw arc of motion was similar before and after the sectioning of the SLIL ($P > .05$). K-wire fixation of the SL interval decreased wrist flexion-extension by an average of 51% ($P < .01$) and radial-ulnar deviation by an average of 57% ($P < .01$) compared with those in normal wrists (Table 1). After staple fixation, wrist flexion-extension through a dart-throw motion decreased by an average of 10.5% ($P < .05$), while radial-ulnar deviation was similar compared with that of normal wrists ($P = .78$).

The isolated range of motion of the scaphoid and lunate during a simulated dart-throw motion after the sectioning of the SLIL ligament showed no significant difference from that of normal wrists ($P > .05$) (Table 2). Range of motion of the scaphoid and lunate after K-wire fixation was significantly decreased compared with that of normal wrists in all planes except for scaphoid flexion ($P < .05$). Lunate flexion after K-wire fixation decreased by 23.7%, and lunate extension decreased by 64.9% compared with measurements for normal wrists ($P < .05$). Scaphoid extension decreased by 95.2% compared with extension in normal wrists ($P < .01$). Conversely, the range of motion of the scaphoid and lunate after staple fixation demonstrated no significant difference from that of normal wrists except in scaphoid extension ($P < .01$), which decreased by 38.3% after staple fixation (Table 2, Fig. 4).

During axial load testing, 3 of the 8 arms demonstrated no failure at maximal load simulating a ground-level fall. Of the 5 arms that failed prior to maximal load, scaphoid waist fractures occurred in 3 arms. None of the scaphoid waist fractures directly involved the staple holes, as the staple was found to be intact without deformity at maximal load or at the time of failure in all arms (Table 3). One arm failed because of a radial styloid fracture, and another arm failed because of a dorsal rim fracture of the distal radius. The average force at failure of the 5 arms that demonstrated failure was 183.5 pounds (range, 101.8–299.7), or an average of 113% (range, 69–158%) of total body weight for the corresponding arms. K-wires in the scaphoid and lunate previously used for marker ball attachment during range of motion testing were removed prior to axial load testing, and no fractures occurred through these K-wire holes.

Discussion

In wrists with an intact SLIL, scaphoid and lunate motion is decreased in a dart-throw motion compared with that in a pure

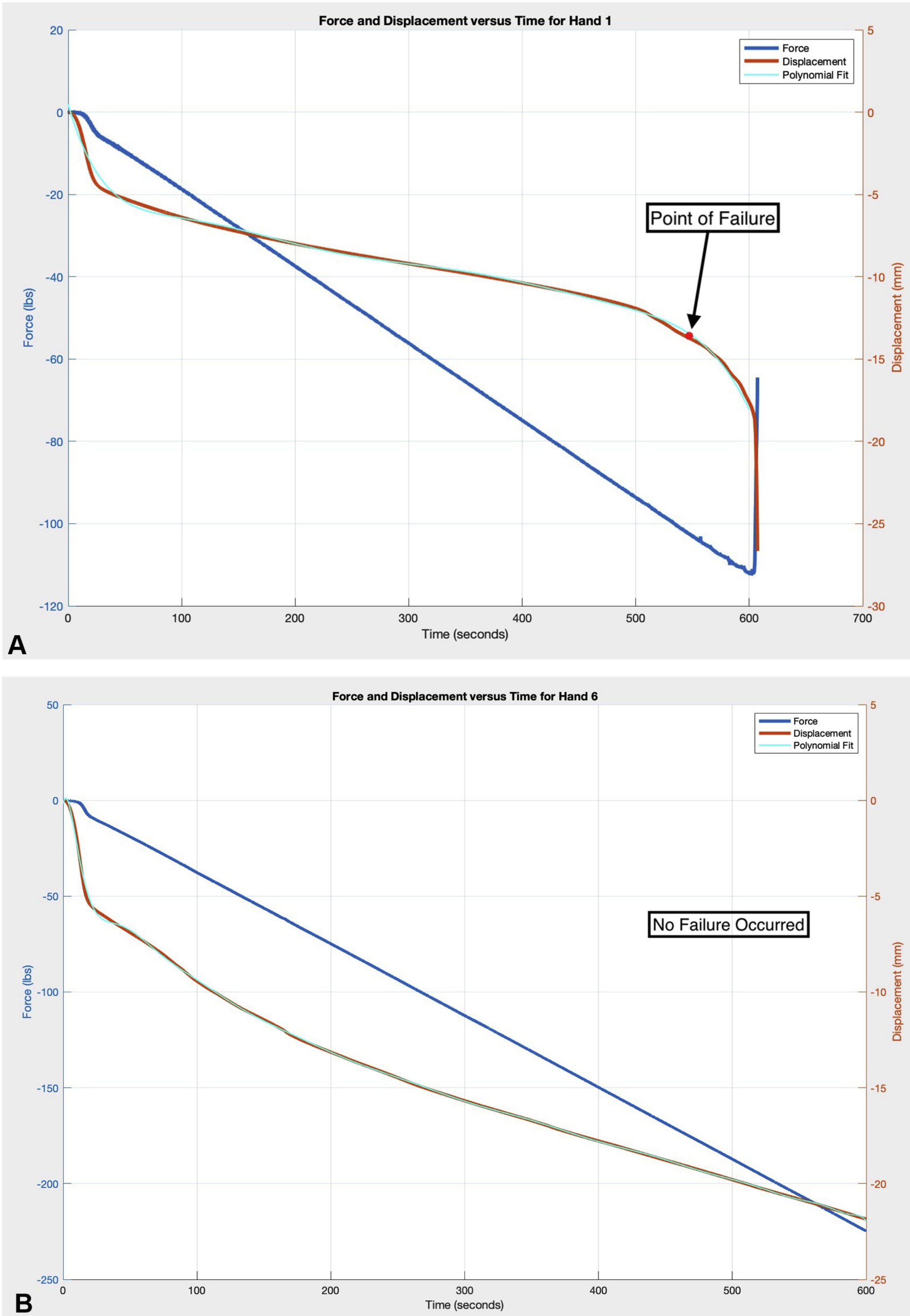

Figure 3. A Force and displacement versus time with Nitinol staple in place demonstrating point of failure. **B** Specimen without failure at maximum force.

wrist flexion-extension arc of motion.[11] However, previous studies have shown that after SLIL injury, the dart-throw motion still results in an increase in the SL interval, indicating the dart-throw motion during early rehabilitation would potentially put stress on the repair of the SLIL.[2] This study showed 2-tine Nitinol staple fixation provided initial stability to the SL interval and

Table 1
Overall Wrist Flexion-Extension and Radial-Ulnar Arc of Motion Through a Dart Thrower's Motion (Degrees)

Specimen	Normal		SLIL Sectioned		K-Wire		Staple	
	Flex-Ext	Rad-Uln Deviation	Flex-Ext	Rad-Uln Deviation	Flex-Ext	Rad-Uln Deviation	Flex-Ext	Rad-Uln Deviation
Arm 1	121	23	116	22	88	19	110	30
Arm 2	101	27	100	27	35	13	89	36
Arm 3	128	26	135	27	41	8	127	16
Arm 4	137	39	148	40	58	27	125	49
Arm 5	77	33	76	31	10	4	66	33
Arm 6	160	48	155	46	85	11	129	53
Arm 7	133	40	137	36	84	16	103	27
Arm 8	138	45	144	48	87	22	142	44
Average	124.4	35.1	126.4	34.6	61	15	111.4	36

Table 2
Range of Motion of Lunate and Scaphoid in Normal Wrists, with SLIL Sectioned, with K-Wire in Place and SLIL Sectioned, and with Nitinol Staple in Place and SLIL Sectioned

Plane of Motion	Normal		SLIL Sectioned			K-Wire			Staple		
	Degrees of Motion		Degrees of Motion	Percent of Normal	*P* Value	Degrees of Motion	Percent of Normal	*P* Value	Degrees of Motion	Percent of Normal	*P* Value
Lunate flexion	30.85	100.0%	30.64	99.32%	.74	23.55	76.34%	.02	35.63	115.49%	.07
Lunate extension	24.18	100.0%	22.45	92.85%	.11	8.48	35.07%	<.001	15.82	65.43%	.11
Lunate pronation	17.04	100.0%	17.59	103.23%	.38	10.31	60.50%	.03	19.83	116.37%	.12
Lunate supination	16.19	100.0%	15.27	94.32%	.19	55.61	343.48%	.01	16.28	100.56%	.97
Scaphoid flexion	54.61	100.0%	56.4	103.28%	.09	57.82	105.88%	.54	54.78	100.31%	.93
Scaphoid extension	44.23	100.0%	45.48	102.83%	.28	2.10	4.75%	<.001	27.29	61.70%	.006
Scaphoid pronation	19.73	100.0%	18.99	96.25%	.08	10.77	54.59%	.002	23.52	119.21%	.06
Scaphoid supination	29.31	100.0%	26.06	88.91%	.63	17.98	61.34%	.01	20.5	69.94%	.29

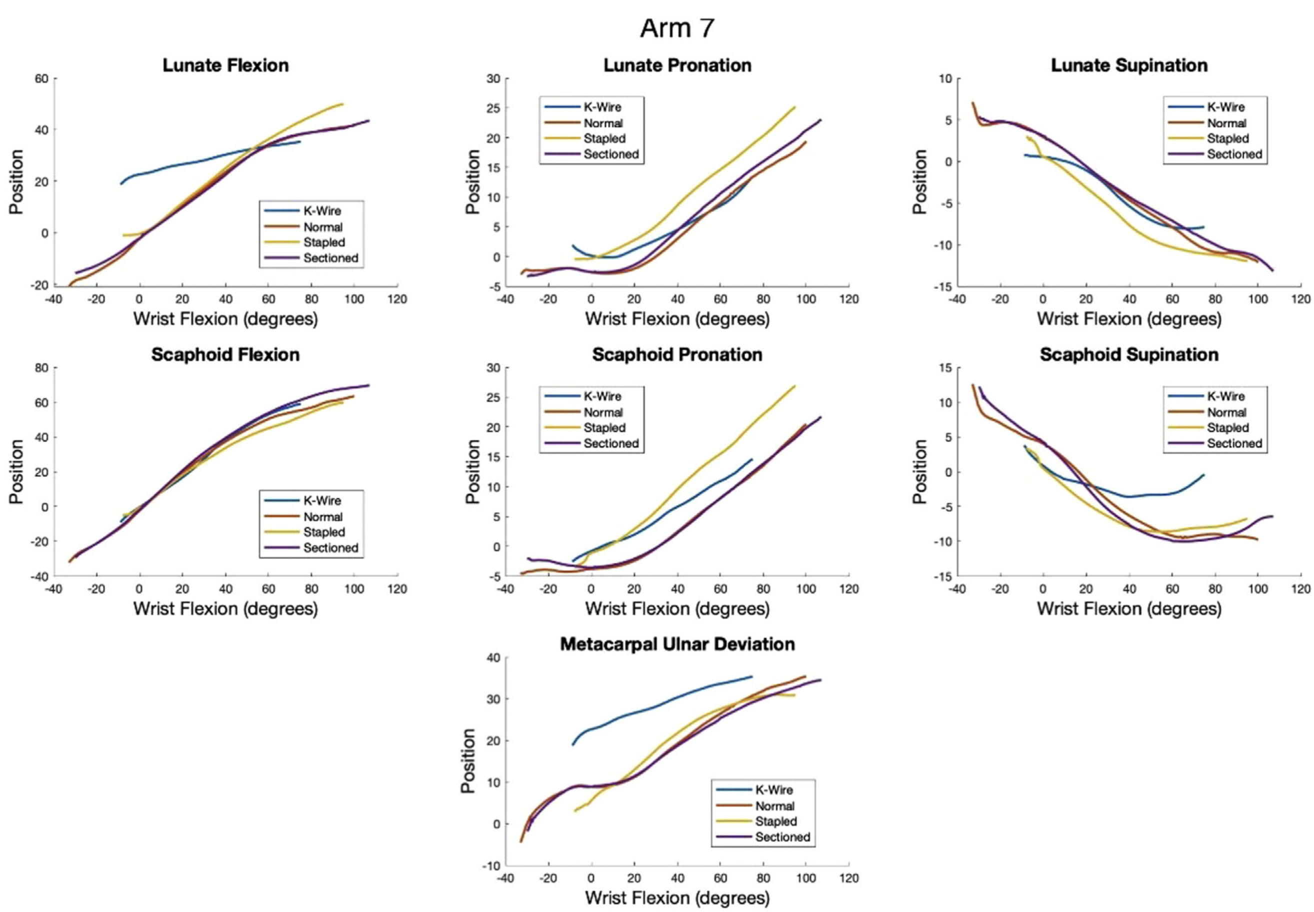

Figure 4. Position of scaphoid and lunate throughout wrist range of motion in normal wrist, after sectioning of SLIL, with K-wire placement and SLIL sectioned, and with staple placement and SLIL sectioned.

Table 3
Load to Failure (in Pounds) and Mode of Failure for Scapholunate Staple Fixation

Specimen	Force (lbs)	Mode of Failure
Hand 1	101.8	Scaphoid fracture
Hand 2	299.7	Radial styloid fracture
Hand 3	No failure	No failure
Hand 4	227.8	Scaphoid fracture
Hand 5	180.3	Distal radius fracture
Hand 6	No failure	No failure
Hand 7	No failure	No failure
Hand 8	108.1	Scaphoid fracture

demonstrated scaphoid and lunate motion in ranges similar to those of normal wrists with an intact SLIL during a simulated dart-throw motion. Staple fixation decreased scaphoid extension by 38.3% compared with that in normal wrists but otherwise maintained similar range of motion of the scaphoid and lunate. Previous studies have shown that the sectioning of the SLIL leads to a 3- to 9-degree increase in scaphoid flexion and an 8- to 19-degree increase in lunate extension during wrist flexion-extension.[1,3] The plane of wrist motion in this study was not a pure flexion-extension wrist motion but included radial and ulnar deviation, which may explain the smaller degrees of change in scaphoid and lunate motion after the sectioning of SLIL. Also, while we attempted to free the marker ball clusters on the scaphoid and lunate from any soft tissues, it is possible that they did impinge, especially at terminal flexion and extension, affecting the ultimate motion data captured.

Fixation of the SL interval with K-wires significantly decreased the range of motion of the scaphoid and lunate compared with normal wrists during a dart-throw motion. K-wire fixation and other popular methods of SLIL repair require long periods of immobilization postoperatively to allow the healing of the repair and because scaphoid and lunate kinematics are disrupted while the K-wires are in place.[4,7,10] Additionally, K-wire fixation has a risk of pin site infection or migration that may lead to articular cartilage damage.[6] Nitinol staple fixation has many advantages over K-wire fixation: it does not violate the articular surface of the scaphoid or lunate, it provides rotational control while allowing more physiologic motion compared with K-wires, and the shape-memory alloy component provides continuous interfragmentary compression.[13,14]

Limitations of the study include those present in many cadaveric studies. The majority of the arms in this study were from the elderly, and degenerative changes that are not typically seen in a younger population were present. However, we obtained x-rays to evaluate for the presence of static diastasis of the SL interval and confirmed the SLIL was intact by direct visualization prior to sectioning. The range of motion data for Arm 1 were averaged over a fewer number of trials than those for the other arms because of malfunction of the motion capture software. This arm still had a trial data set for the full range of motion tested and thus was included in the study.

The SLIL was not repaired after sectioning when the K-wire or staple was used as fixation. Our rationale to not repair the ligament was to attempt to best isolate the effect that the staple had in stabilizing the scapholunate interval. In a true clinical setting, the staple fixation would likely be used to augment a repair of the SLIL after an acute injury, and the biomechanics of this combined procedure would be another area of interest for future study.

The bone quality in this cadaver model may have also contributed to the fractures seen on axial load testing, but the scaphoid fractures that occurred were scaphoid waist fractures that did not involve the staple holes or result in deformity of the staple. The small number of cadavers limited the ability to test load to failure with K-wires in place and compare this procedure with the staple fixation, but such a comparison would be an area of future interest. Additionally, the K-wires were left outside the scaphoid and lunate as they would be in a clinical setting. Soft tissue tethering from the K-wires was noted to be minimal but could have potentially limited wrist range of motion. Finally, we were unable to measure or account for the effects of hysteresis on the wrist throughout the arc of motion tested.

Based on our range of motion and axial load testing results, 2-tine Nitinol staple fixation more closely maintains physiologic motion of the scaphoid and lunate during a dart-throw motion compared with that of K-wire fixation. Therefore, after a period of postoperative immobilization, staple fixation has the potential to allow earlier range of motion in the postoperative rehabilitation of these patients. However, prior to the recommendation of earlier range of motion in clinical practice, future studies evaluating cyclical testing of the staple are needed to determine the ability of staple fixation to maintain the integrity of SLIL repair over time.

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