SCIENTIFIC ARTICLE

Biomechanical Effects of Radioscapholunate Fusion With Distal Scaphoidectomy and Triquetrum Excision on Dart-Throwing and Wrist Circumduction Motions

Daisuke Suzuki, MD,*† Shohei Omokawa, MD, PhD,‡ Akio Iida, MD, PhD,§ Yasuaki Nakanishi, MD, PhD,† Hisao Moritomo, MD, PhD,|| Pasuk Mahakkanukrauh, MD, PhD,¶# Yasuhito Tanaka, MD, PhD†

Purpose Distal scaphoid and triquetrum excisions can improve the range of wrist motion after radioscapholunate (RSL) fusion, but little is known about the kinematics of dart-throwing and global circumduction motions. We hypothesized that these excisions could increase the range of motion without causing midcarpal instability.

Methods Seven fresh-frozen cadaver upper extremities were mounted on a testing apparatus after isolation and preloading of the tendons of the flexor carpi radialis, flexor carpi ulnaris, extensor carpi radialis, and extensor carpi ulnaris. Sequential loadings of the flexor carpi ulnaris and extensor carpi radialis simulated active dart-throwing motion. Passive circumferential loading produced the wrist circumduction motion. We measured the range of wrist motions with an electromagnetic tracking system in 4 experiments: intact, simulated RSL fusion, RSL fusion with distal scaphoid excision, and RSL fusion with distal scaphoid and total triquetrum excisions. To evaluate midcarpal stability, we conducted passive mobility testing of the distal carpal row in the radial, volar, ulnar, and dorsal directions.

Results Radioscapholunate fusion decreased the dart-throwing motion to a mean of 46% of the baseline value; distal scaphoid and triquetrum excisions increased the mean arc to 50% and 62%, respectively. Radioscapholunate fusion diminished the wrist circumduction to a mean of 43% of the baseline value, which increased to a mean of 58% and 74% after distal scaphoid and triquetrum excision, respectively. A significant increase in radial deviation was noted after distal scaphoid excision, and subsequent triquetrum excision significantly increased motion in the ulnar-palmar direction. Regarding midcarpal stability, dorsal translation significantly increased after distal scaphoid and triquetrum excisions.

Conclusions Distal scaphoid and triquetrum excision after RSL fusion improved both dart-throwing and circumduction motions, but dorsal midcarpal instability occurred.

Clinical relevance Subsequent carpal excisions may improve short-term outcome by increasing motions in a RSL-fused wrist; however, a potential risk of midcarpal instability should be considered. *(J Hand Surg Am. 2021;46(1):71.e1-e7. Copyright © 2021 by the American Society for Surgery of the Hand. All rights reserved.)*

Key words Biomechanics, carpal bone excision, dart-throwing motion, radioscapholunate fusion, wrist circumduction motion.

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*From the *Department of Orthopaedic Surgery, Nishi-Nara Central Hospital; the †Department of Orthopaedic Surgery; the ‡Department of Hand Surgery, Nara Medical University; the §Department of Orthopaedic Surgery, Hanna Central Hospital, Nara; the ||Yukioka Hospital Hand Center, Osaka Yukioka College of Health Science, Osaka, Japan; the ¶Excellence in Osteology Research and Training Center (ORTC); and the #Department of Anatomy, Faculty of Medicine, Chiang Mai University, Chiang Mai, Thailand.*

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Corresponding author: Shohei Omokawa, MD, PhD, Department of Hand Surgery, Nara Medical University, 840, Shijo-cho, Kashihara, Nara 634-8521, Japan; e-mail: omokawa@gaia.eonet.ne.jp.

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RADIOSCAPHOLUNATE (RSL) FUSION IS INDICATED for treatment of radiocarpal arthritis.[1,2] Although this procedure preserves midcarpal motion, persistent limitation of wrist range of motion is inevitable.[3–5] Additional procedures to improve post-RSL fusion motion have included excisions of the distal scaphoid and entire triquetrum.[6,7]

Dart-throwing motion is important in daily use of the wrist and mainly involves the midcarpal joint.[8] Wrist circumduction without simultaneous forearm rotation traces an oval shape as analyzed by *in vitro*[9,10] and *in vivo*[11] studies, and this oval motion involves a physiological axis of wrist motion in the dart-throwing plane rather than in the orthogonal flexion-extension or radioulnar deviation planes. Therefore, analyzing dart-throwing and circumduction motion is useful for evaluating wrist performance.

Most previous studies have investigated wrist movement in the orthogonal flexion-extension and radioulnar deviation planes.[12–14] Although distal scaphoid and triquetrum excision is known to improve orthogonal wrist movement after RSL fusion,[6,7] no information is available regarding their effect on dart-throwing and circumduction motion of the wrist. In addition, it is unclear how this procedure affects midcarpal stability. The purpose of this study was to evaluate, in cadaver wrists, the biomechanical effects of distal scaphoid and total triquetrum excision on the range of dart-throwing and circumduction motion in the RSL-fused wrist and to evaluate the potential for midcarpal instability after excision.

MATERIALS AND METHODS

Seven fresh-frozen cadaver arms from 2 men and 5 women averaging 60 years of age were used for this study. None of the specimens had a history of carpal injury or wrist problems. All wrists were thawed to room temperature overnight in advance of testing. After removal of the skin and subcutaneous tissue, the flexor carpi ulnaris (FCU), flexor carpi radialis, and extensor carpi ulnaris tendons were dissected and each of their ends sutured to form a loop. The extensor carpi radialis longus and brevis (ECRL/B) were sutured to each other to form their own loop. We preserved the joint capsule and extrinsic and intrinsic ligaments of the wrist and the interosseous membrane. The midcarpal shift test did not show any midcarpal instability in any of the specimens.[15] We confirmed that there was no degenerative change in the midcarpal joint by opening the joint using a modified Berger-Bishop approach,[16] and then the dorsal capsule was repaired using 4-0 Vicryl suture (Polygalactin 910; Ethicon, Somerville, NJ).

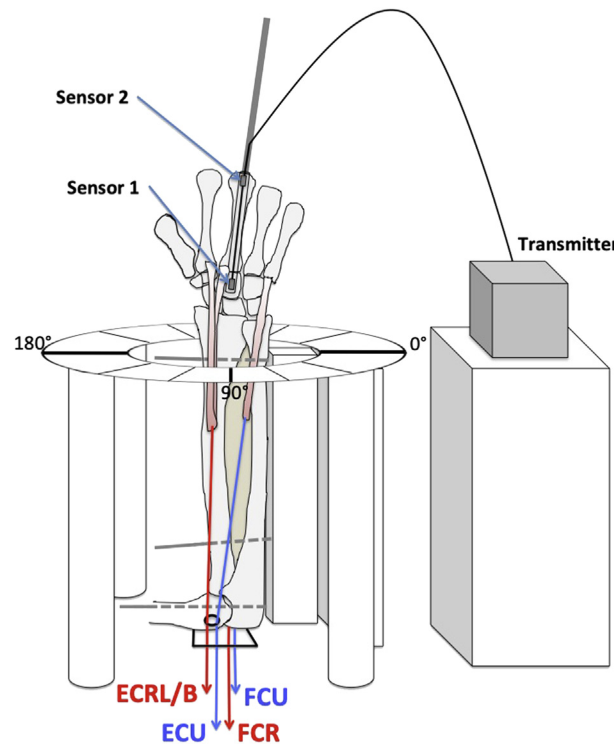

FIGURE 1: Experimental setup and positioning of sensors. Each above-elbow specimen was mounted onto a custom-designed testing frame with 1.8-mm-diameter K-wires drilled through the radius and ulna to maintain the neutral forearm rotation. One sensor each was fixed at the dorsal surface of the capitate and the third metacarpal head. Two sensors were aligned in parallel to the third metacarpal shaft. Both sensors were fixed to the bone using nylon tubes and plastic cable ties.

Each above-elbow specimen was mounted onto a custom-designed testing frame with 1.8-mm-diameter K-wires drilled through the radius and ulna to maintain neutral rotation of the forearm (Fig. 1). The flexors were converged to the medial epicondyle, and extensors were converged to the lateral epicondyles. In the manner established by Patterson et al, [17] the flexor carpi radialis and ECRL/B loops, and the FCU and extensor carpi ulnaris loops were connected by wires that ran through 2 floating pulleys (Fig. 2A). One pulley was attached to the radial extensor-flexor tendon pair and the other to the ulnar extensor-flexor tendon pair. For physiological loading, 0.45-kg weights were applied to each pulley arrangement, one to the extensors and flexors on the radial side and the other to the ulnar side.[17]

An electromagnetic tracking device (TrakSTAR; Ascension Technologies, Burlington, VT) was used to collect 3-dimensional position data. One sensor each was fixed at the dorsal surface of the capitate

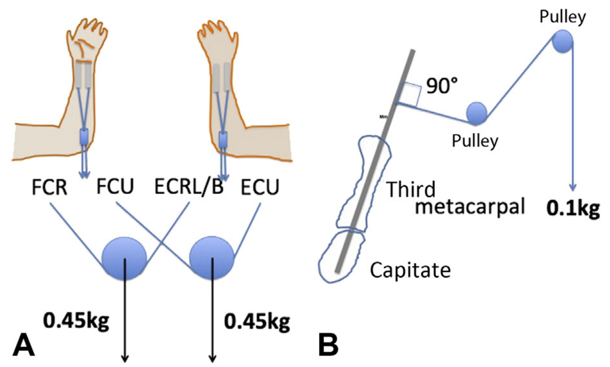

FIGURE 2: The apparatus for physiological loading and the measurement of passive circumduction motion. **A** The flexor carpi radialis (FCR) and ECRL/B loops, and the flexor carpi ulnaris (FCU) and extensor carpi ulnaris (ECU) loops were connected by wires that run through the 2 floating pulleys; 0.45-kg weights were applied to each pulley arrangement as physiological loading. **B** A wooden rod was inserted into the third metacarpal and capitate intramedullary space as a traction pole for passive motions. Passive circumduction motion was reproduced by pulling the wooden rod perpendicular to its inclination using 2 floating pulleys and applying a load of 0.1 kg. The range of passive circumduction motion was recorded circumferentially in 12 directions.

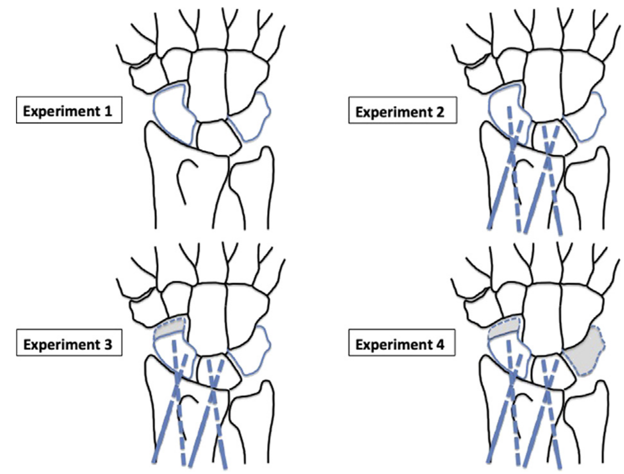

FIGURE 3: Schematic drawing of simulated surgical procedures. Experiment 1: intact wrist; experiment 2: simulated RSL fusion; experiment 3: RSL fusion with distal scaphoidectomy; experiment 4: RSL fusion with distal scaphoid and triquetrum excision.

and the third metacarpal head. We set 2 sensors aligned in parallel to the third metacarpal shaft (Fig. 1). Angles between the 2 sensors were measured to calculate the ranges of motion. A wooden rod was inserted into the third metacarpal and capitate intramedullary space as a traction pole for passive motions.

We evaluated both active dart-throwing and passive circumduction range of motion under physiological loading as described previously Simulated active dart-throwing motion was reproduced by an additional 0.225 kg loading of the FCU and ECRL/B. Loading of the FCU reproduced the motion in the ulnar-palmar direction and loading to ECRL/B reproduced the motion in the radiodorsal direction. Passive circumduction motion was reproduced by pulling the wooden rod perpendicular to its inclination using 2 floating pulleys and applying a load of 0.1 kg (Fig. 2B). We measured the range of motion in 12 directions, set 30° apart on an axial plane. Ulnar deviation, extension, radial deviation, and flexion corresponded to 0°, 90°, 180°, and 270°, respectively. We measured simulated active dart-throwing motion and passive circumduction motion for each specimen in each of 4 experiments: intact wrist; simulated RSL fusion; RSL fusion with distal scaphoid excision; RSL fusion with excision of the distal scaphoid and total triquetrum.

The range of passive circumduction motion was compared with the baseline (intact wrist) as an average ratio of motions in 12 directions.

To represent the fused state, the radiocarpal joint was fixed by placing 2 K-wires, 1.6 mm in diameter, across both the radioscaphoid and the radiolunate joints (Fig. 3). The fixation was placed to immobilize the lunate and scaphoid in neutral position without any appreciable coronal or sagittal deviation. The wrist then underwent excision of the distal scaphoid. The bone excision was performed parallel to the axial plane at a depth of 5 mm from the scaphotrapeziotrapezoid joint interval using a 2.5-mm arthroscopic bur through a modified Berger-Bishop approach.[15] The triquetrum excision was performed using an arthroscopic bur and a number 15 scalpel blade through an additional 10-mm longitudinal incision in the ulnar capsule. We preserved the volar and dorsal capsular ligaments, except those in the attachment sites to the triquetrum. The joint capsule was sutured in each experiment to maintain the integrity of the capsuloligamentous structures.

Evaluation of midcarpal stability

An additional 8 fresh-frozen cadaver arms were used for this part of the study. This group consisted of upper extremities from 5 men and 3 women averaging 74 years of age. Dissection, setup, and physiological loading were conducted in the same manner as in the other experiment. We confirmed that there was no degenerative change or instability in the midcarpal joint before the experiment by direct inspection as described previously. Two sensors were fixed at the dorsal aspect of the third metacarpal base and distal radius. A traction force was applied to the capitate toward perpendicular to the axis of the capitate with a load of 20 N in 4 directions (dorsal, radial, volar, and ulnar), while maintaining the wrist in neutral position. The third metacarpal and the capitate bone were fixed by an intramedullary rod. For quantifying midcarpal instability, we measured the magnitudes of translation of the third metacarpal base relative to the radius. The measurements were conducted in each specimen in 3 experiments: simulated RSL fusion; RSL fusion with distal scaphoid excision; RSL fusion with excision of the distal scaphoid and total triquetrum.

Statistical analysis

The ranges of simulated active dart-throwing motion arc, passive circumduction motion, and midcarpal instability were analyzed. We evaluated the differences between each of the experiments using repeated measures analysis of variance and multiple comparison tests (Holm-Bonferroni method). A P level of less than .05 was considered statistically significant. We performed a pilot study to assist in sample size calculation. Four specimens were evaluated. A sample size estimation was performed with power set at 80% and a significance level of .05. Based on a previous kinematic study of wrist motion during selected functional tasks in healthy individuals,[18] the expected outcome is considered to be greater than 61° of active dart-throwing motion arc after subsequent carpal excisions. The mean difference in arc between 61° and acquired angle after RSL fusion was 4.3° with a standard deviation of 3.4°. The mean difference in magnitude of dorsal midcarpal translation between RSL fusion and subsequent distal scaphoid and triquetrum excision was 1.0 mm, with an SD of 0.9 mm. These were determined as the expected differences. We found that 6 and 7 specimens were needed to detect difference in dart-throwing motion and dorsal midcarpal translation, respectively. Therefore, we used the current study design with a sample size of 7 and 8 specimens for each experiment.

RESULTS

Simulated active dart-throwing motion and passive circumduction motion

The average range of dart-throwing motion was 125°, 58°, 63°, and 78°, from intact to RSL fusion with excision of the distal scaphoid and total triquetrum, respectively. After RSL fusion, the arc of dart-throwing motion significantly decreased to a mean of 46% of the intact wrist ($P < .05$). After the addition of distal scaphoid excision, the arc increased to 50% of the intact wrist. Triquetrum excision further increased the range of motion to 62% of the intact wrist, and significant differences were noted compared with RSL fusion ($P < .05$) and distal scaphoid excision ($P < .05$) (Fig. 4). The averaged axis of the dart-throwing path was located at 112° (radiodorsal direction) and 310° (ulnar-palmar direction).

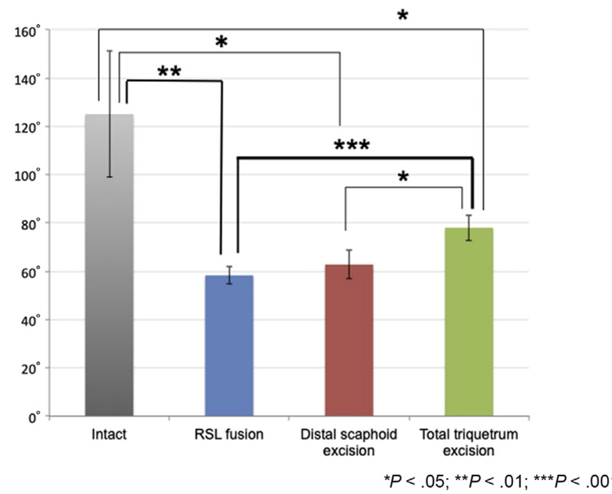

FIGURE 4: The average range of simulated active dart-throwing motion. After RSL fusion, the arc of dart-throwing motion significantly decreased to a mean of 46% of that of the intact wrist. After the addition of distal scaphoid excision, the arc increased to 50% of that of the intact wrist. Triquetrum excision further increased the range of motion to 62% of that of the intact wrist, a significant difference compared with RSL fusion and distal scaphoid excision.

Passive circumduction range of motion was reduced by RSL fusion to a mean of 43% of the baseline value. Subsequent excision of the distal scaphoid and triquetrum increased the range of circumduction to 58% and 74% of the baseline, respectively (Fig. 5). Radioscapholunate fusion significantly decreased the ranges of motion in 11 directions except that in a 240° radiopalmar direction ($P < .05$). Distal scaphoid excision significantly increased the ranges of motion in 150°, 180°, and 210° (radial directions) compared with RSL fusion ($P < .05$). Additional triquetrum excision significantly increased the range of motions in 300°, 330°, and 0° (ulnar-palmar directions) compared with distal scaphoid excision alone ($P < .05$).

Evaluation of midcarpal stability

Translation of the third metacarpal relative to the radius increased in accordance with experiment progression in 4 directions (dorsal, radial, palmar, and

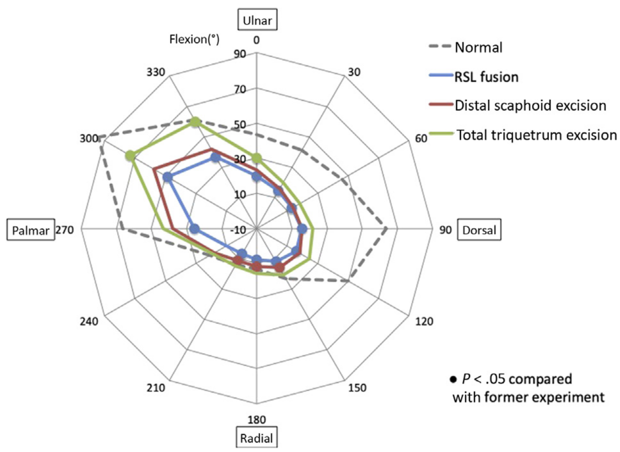

FIGURE 5: The average ranges of passive circumduction motion. Passive circumduction range of motion was significantly diminished by RSL fusion in 11 directions except in a 240° radiopalmar direction ($P < .05$). Subsequent distal scaphoid and triquetrum excision improved the range of circumduction while maintaining its elliptical shape. Distal scaphoid excision significantly increased the range of motions in 150°, 180°, and 210° (radial direction) compared with RSL fusion ($P < .05$). Additional triquetrum excision significantly increased the range of motions in 300°, 330°, and 0° (ulnar-palmar directions) compared with distal scaphoid excision alone ($P < .05$)

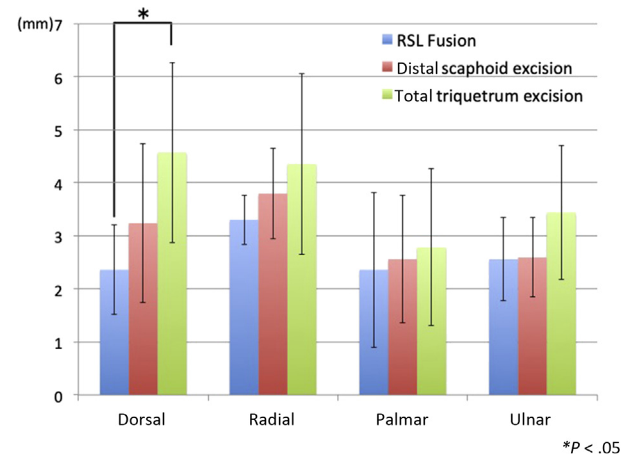

FIGURE 6: Magnitude of midcarpal translation in each of the 4 (dorsal, radial, volar, and ulnar) directions. Translation of the third metacarpal bone relative to the radius increased in accordance with experiment progression in 4 directions. Significant dorsal translation occurs by additional triquetrum excision ($P < .05$).

ulnar) (Fig. 6). After subsequent excision of the distal scaphoid and triquetrum, the averaged dorsal translation was 4.6 mm, which was significantly increased compared with RSL fusion (2.4 mm) ($P < .05$). No significant change was noted in the radial, volar, and ulnar directions.

DISCUSSION

This study demonstrated that distal scaphoid and triquetrum excisions after RSL fusion improved the range of simulated active dart-throwing and passive circumduction motion. Because both the dart-throwing and the circumduction motions are essential to accomplish the activities of daily living, subsequent distal scaphoid and triquetrum excisions potentially improve function of the wrist after RSL fusion.

Although RSL fusion decreased the arc of dart-throwing and circumduction motion to a mean of 46% and 43% of the baseline value, subsequent carpal excisions increased the dart-throwing and circumduction arc to 50% and 62%, and 58% and 74%, respectively. These findings are in agreement with previous clinical reports.[3–5] The average range of passive motion for RSL-fused wrists was 41° of the flexion-extension arc and 27° of the radioulnar deviation arc. In clinical series of RSL fusions, the average flexion-extension arc was 50° and the radioulnar deviation arc was 24°. After additional resection, the range of motion was found to increase to 65° of the flexion-extension arc, and 46° of the ulnoradial deviation arc. Bain et al[7] reported 23 patients who underwent RSL fusion and subsequent distal scaphoid and entire triquetrum excision. The postoperative flexion-extension arc averaged 57° and the mean ulnoradial deviation arc was 43°. The current experimental model provided results similar to these clinical outcomes,[3–5,7] suggesting that preserving the joint capsule and ligament structures and applying physiological loads can represent actual clinical situations.

Pervaiz et al[13] postulated that removal of both the distal scaphoid and the distal triquetrum converts the complex midcarpal joint into a simple ball-and-socket joint. Our observations revealed that excision of the carpal bones improved wrist circumduction motion while maintaining its elliptical shape within the dart-throwing axis.

Distal scaphoid excision extended the circumduction motion, especially in the radial direction. The distal facet of the scaphoid tubercle is a mechanical block and serves to constrain movement of the trapezium and trapezoid bones in the radial direction. In comparison with the previous research in cadavers,[10–12] the loss of motion after RSL fusion was relatively larger, and improvement following resection of the scaphoid and triquetrum was smaller in the current study. Our model attempted to simulate an arthroscopic procedure by preserving soft tissue structures around the midcarpal joint. The minimum distal scaphoid resection (5 mm) may also have influenced the results. As reported by Garcia-Elias et al,[6] we recommend avoiding distal scaphoid resection of larger than one-quarter of its length in the clinical setting, because excessive distal scaphoidectomy may lead to subluxation of the capitate relative to the scaphoid during ulnar deviation motion.

Additional triquetrum excision extended circumduction mostly in the ulnar and palmar direction. We postulate that triquetrum excision had 2 different effects on midcarpal joint kinematics on the basis of osseous and ligamentous anatomy and function. Kamal et al[19] measured the *in vivo* kinematics of the triquetrum-hamate joint as the wrist moves along the dart-throwing path. They suggested that ulnar flexion was constrained by the triquetrum-hamate joint. The concave distal ridge of the hamate guides the triquetrum toward the hook of the hamate, which blocks further ulnar flexion of the wrist. The other effect is related to the function of the intrinsic ligaments. Calfee et al[20] analyzed altered midcarpal kinematics after simulated RSL fusion using cadaver wrists and showed that triquetrohamate joint rotation increased during wrist flexion-extension motion. Because the triquetrum has insertions of dorsal intercarpal and palmar triquetral-hamate ligaments, we speculate that triquetrum excision may further increase the rotatory motion of distal carpal row, leading to an increase in the range of midcarpal motion.

Midcarpal instability is a potential risk after distal scaphoid and triquetrum excision. Bain et al[7] reported that no midcarpal dislocation or secondary degeneration occurred in their case series. Pervaiz et al[13] observed no distal row instability in any of their test specimens, all of which were stressed under live fluoroscopy to check for instability, but they did not conduct a quantitative analysis. Our study showed that significant dorsal translation occurred after excision of the distal scaphoid and triquetrum compared with that of RSL fusion alone. Triquetrum excision results in detachment of the proximal insertion of palmar triquetral-hamate-capitate ligaments and may lead to dorsal midcarpal instability.[21] We believe surgeons should be cognizant of the potential for dorsal midcarpal instability following triquetrum excision in the RSL-fused wrist. Although the integrity of the palmar ulnocapitate ligament may prevent dorsal dislocation of the distal carpal row, our findings showing significant change in midcarpal kinematics suggests the possible need for postoperative immobilization after this procedure.

This study has several limitations. First, as is the case with all cadaver studies, we could not fully mimic the surgical procedure or estimate postoperative soft tissue responses. Pinning of the intact lunate and proximal pole of the scaphoid to the radius does not fully replicate the RSL fusion where the metaphyseal region of the radius is shelled out and the denuded lunate and proximal pole of scaphoid are inset. In the clinical *in vivo* situation, additional triquetrum excision may lead to more soft tissue stiffness around the joint than that with excision of the distal pole of the scaphoid in RSL-fused wrists. Second, we were not able to assess the stability of midcarpal joint before RSL fusion. Although a manual shift test was carried out, the reliability of the test is uncertain. Evaluating motion between the capitate and the lunate in intact wrists may be desirable, but our pilot study revealed that sensor setting to the lunate bone was quite unstable and collecting data was difficult. Third, we could not evaluate the influence of lunotriquetral ligament injury, which is commonly observed in patients with radiocarpal arthritis following trauma and scapholunate advanced collapse wrist with preserved midcarpal articular cartilage. A biomechanical study has shown that simulated RSL fusion altered lunotriquetral joint kinematics during wrist flexion-extension motion.[20] Repeating the study with simple release of the lunotriquetral ligaments is warranted to understand the effect of an increase in midcarpal joint motion after RSL fusion. Fourth, the current study did not clarify the long-term effect of the additional procedure of excisional arthroplasty. Midcarpal instability is a potential risk of this procedure, however; further *in vivo* investigations are necessary. Finally, the current study could not establish the active wrist circumduction motion; however, the passive circumduction analyses provided novel kinematic information.

In conclusion, distal scaphoid and triquetrum excision improved both dart-throwing and circumduction wrist motions by converting the midcarpal joint into an elliptical form. Additional triquetrum excision may decrease midcarpal stability.

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