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SCIENTIFIC ARTICLE

The Biomechanical Effects of Simulated Radioscapholunate Fusion With Distal Scaphoidectomy, 4-Corner Fusion With Complete Scaphoidectomy, and Proximal Row Carpectomy Compared to the Native Wrist

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Purpose To determine the effect of simulated radioscapholunate fusion with distal scaphoid excision (RSLF+DSE), 4-corner fusion with scaphoidectomy (4-CF), and proximal row carpectomy (PRC) on the wrist's range of motion (ROM), contact pressure, and contact force in a cadaveric model.

Methods Ten freshly frozen cadaveric wrists were tested under 4 sequential conditions: native wrist, RSLF+DSE, 4-CF, and PRC. The simulated fusions were performed using two 1.6-mm Kirschner wires. The ROM in the flexion-extension and radioulnar deviation planes was evaluated. Contact area, contact pressure, and contact force were measured at the scaphocapitolunate joint for the RSLF+DSE simulation and radiocarpal joint for the 4-CF and PRC simulations. Mechanical testing was performed using a 35-N uniaxial load and pressure-sensitive film.

Results The RSLF+DSE and 4-CF groups had a decreased wrist arc ROM compared with the native wrist. The PRC group had a greater wrist arc ROM compared with the RSLF+DSE and 4-CF groups, but compared to the native wrist, it demonstrated a mildly decreased wrist arc ROM. The carpal pressure and contact force were significantly increased in the RSLF+DSE, 4-CF, and PRC groups compared with those in the native wrist. The RSLF+DSE group had the smallest increase in the carpal pressure and contact force, whereas the PRC group had the greatest increase.

Conclusions Our study validates previous findings that PRC is motion-conserving but has the greatest contact force, whereas RSLF-DSE and 4-CF may cause a decrease in the ROM but have lower contact forces.

Clinical relevance Understanding the underlying native wrist biomechanics and alterations following different surgical treatments may assist hand surgeons in their clinical decision making for the treatment of stage II scapholunate advanced collapse. *(J Hand Surg Am. 2021;46(12):1125.e1-e8. Copyright © 2021 by the American Society for Surgery of the Hand. All rights reserved.)*

Key words 4-corner fusion, proximal row carpectomy, radioscapholunate fusion, scapholunate advanced collapse, wrist biomechanics.

Online Exclusive

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Scapholunate advanced collapse (SLAC) is a condition characterized by progressive instability and deformity that leads to advanced arthritic disease affecting the radiocarpal and midcarpal joints.[1] Scapholunate advanced collapse affects 55% of individuals with osteoarthritis of the wrist and develops secondary to an inciting event, either traumatic or atraumatic, that results in scapholunate dissociation and altered kinematics.[2–4] Watson and Ballet,[3] in their original classification of SLAC, noted the characteristic progression of the disease using radiography. Stage I involves the distal scaphoid and radial styloid, stage II involves the entire radioscaphoid joint, and stage III involves the scaphocapitate and/or capitolunate joint.[3,5] Patients with pain who have failed nonsurgical management are eligible for surgical intervention.

Different surgical treatments have been described for stage II SLAC. Radioscapholunate arthrodesis with distal scaphoidectomy (RSLF+DSE), 4-corner fusion with complete scaphoidectomy (4-CF), and proximal row carpectomy (PRC) are procedures that address radiocarpal arthrosis, often with favorable outcomes.[6–22] Although 4-CF and PRC have been well described with good results and, hence, have been used commonly, RSLF+DSE has been less studied and used. This may be secondary to the argument that RSLF+DSE is more destructive than 4-CF and, compared with PRC, requires healing after arthrodesis.[13–17]

Although good clinical results have been reported for each of these procedures, there is a lack of data directly comparing the biomechanics of these techniques. Our study aimed to compare the joint contact forces of the principal wrist articulation after each of these procedures. We hypothesized that the cadaveric wrist contact pressures at the scaphocapitolunate articulation following RSLF+DSE, radiolunate joint following 4-CF, and proximal capitate following PRC are equal.

MATERIALS AND METHODS

Ten freshly frozen, human cadaveric wrist specimens (7 female and 3 male) without evidence of arthritis or instability were obtained from the Body Donation Program of the University of California, Davis. Radiographic evaluation was performed to assess for radiocarpal arthrosis, midcarpal arthrosis, and an underlying skeletal abnormality. Specimens with arthritic disease and/or osseous abnormalities were excluded from the study. Each cadaveric specimen was transected at the level of the proximal forearm after thawing overnight at 4 °C. The superficial soft tissues, flexor tendons, extensor tendons, distal radioulnar joint, and interosseous membrane were kept intact to replicate the native anatomy and biomechanics. The digits were disarticulated at the metacarpophalangeal joint, and two 3.2-mm Kirschner wires were inserted into the proximal end of the radius and ulna. A 2.8-mm Kirschner wire was inserted into the third metacarpal. The specimens were embedded in polymethylmethacrylate (GC America) within a cylindrical polyvinyl chloride mold to allow for axial load testing. A dorsal, ligament-sparing capsulotomy was performed to confirm that there was no evidence of midcarpal arthrosis or an intercarpal ligament injury.[23,24] All the dissections and simulated procedures were performed by a fellowship-trained hand surgeon in conjunction with a senior orthopedic resident.

Mechanical testing was performed under 4 conditions on each specimen: a native cadaveric wrist with all carpal bones intact, RSLF+DSE, 4-CF, and PRC. Each technique was performed on the wrist through a dorsal ligament-sparing approach. The dorsal capsule was sutured using 2-0 Ethibond (Ethicon, Johnson & Johnson) in an interrupted, figure-of-eight fashion after each simulated technique and prior to testing. The simulated procedures were performed sequentially, followed by subsequent mechanical loading and range-of-motion (ROM) testing. Each technique for the purpose of this study is described below.

Measurement of ROM

The ROM in the flexion-extension and radioulnar deviation planes was measured as previously described by Bain et al.[14] The forearm was clamped and secured to the table, allowing the wrist to hang freely. A 1.5-kg traction weight was attached to the third metacarpal head for the assessment of flexion and extension (Fig. 1). The traction weight was then attached to the second metacarpal head for the measurement of ulnar deviation and the fourth metacarpal head for the measurement of radial deviation. A wrist-specific goniometer centered at the level of the proximal capitate and aligned proximally with the forearm and distally with the metacarpal was used to measure wrist motion. Three separate trials were conducted, and the ROMs were averaged for each specimen in each motion plane. The summation of the ROMs of each plane resulted in the arc-of-motion calculation.

Measurement of contact pressure

The method of measuring contact pressure and contact area has been previously described.[25] The dorsal capsulotomy was performed, and a pressure-sensitive

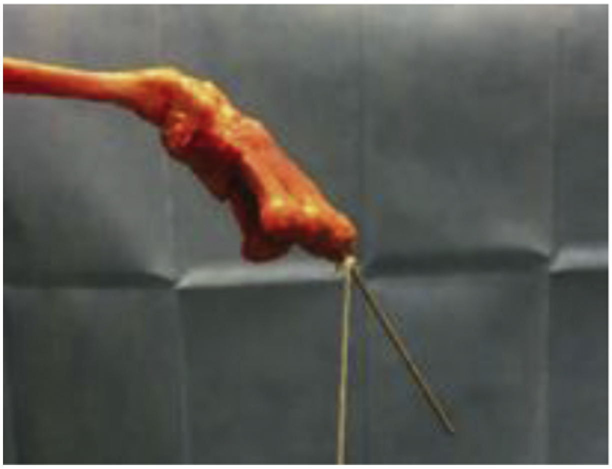

FIGURE 1: Image depicting the technique for simulating wrist flexion using a traction weight applied to the third metacarpal.

FIGURE 2: Fluoroscopic image demonstrating the simulation of an RSLF+DSE. K-wire fixation of the radioscapholunate joint was performed with the addition of a DSE.

film (Fujifilm Prescale) was placed within the radiocarpal or midcarpal joint depending on the primary articulation assessed. The pressure was measured at both the midcarpal and radiocarpal joints in the native specimen. The film was placed in the midcarpal joint for the RSLF+DSE simulation group and radiocarpal joint for the 4-CF and PRC simulation groups. In order to maintain consistency and limit confounding variables, a strip of equal length was placed for each test. This resulted in a strip that encompassed both the scaphoid and lunate facets of the radius for proximal measurements (radiocarpal joint measurement in the native specimen, radiolunate joint measurement in the 4-CF simulation specimen, and capitoradial joint measurement in the PRC simulation specimen). This resulted in a strip that encompassed the entire length of the midcarpal joint (distal scaphoid, distal lunate, and distal triquetrum) for midcarpal joint measurements in the native specimen and scaphocapitolunate articulation in the RSLF+DSE simulation specimen. An ultralow-scale pressure-sensitive film was used based on previous studies.[25,26] The film was protected from fluid and sealed in a polyvinyl chloride film, as previously described.[24,27] After loading the film in a controlled manner and confirming its stability within the joint, the dorsal capsulotomy was repaired. The embedded proximal and distal ends of the specimen were placed in a mechanical loading system (Material Test System 858) with a 445-N load cell (Honeywell). Force was applied to the third metacarpal in a direction collinear to the long axis of the radius and ulna until a 35-N reaction force was recorded at the load cell. This force was held for 30 seconds and then released.[25] Film migration was monitored, and if migration occurred, the test was aborted and repeated using a new film. Following the mechanical testing of the various cadaveric groups, the pressure-sensitive film was removed, digitally scanned (Epson 4990), and converted to gray-scale images. The region with the highest density was identified to account for an axial load and thus mitigate the analysis of shear stresses. A standard software package (ImageJ/Fuji) was used to measure the contact area and pressure values, allowing for the calculation of the contact force in the radiocarpal or midcarpal joint.[28] Separate trials were conducted, and the values were averaged for each specimen.[24]

Method for the simulation of RSLF+DSE

An RSLF was simulated using 1.6-mm Kirschner wires (Fig. 2). An osteotome was used to compress the lunate, ensuring that it was held in a neutral position within the radiolunate fossa. One 1.6-mm Kirschner wire was then inserted into the dorsal aspect of the distal radius and into the body of the lunate. In a similar fashion, the scaphoid was fixed to the scaphoid fossa of the radius using one 1.6-mm Kirschner wire.[15] An osteotomy was then performed to excise the distal scaphoid at the level of the scaphoid waist distal to the implants. Capsular and ligamentous attachments in close proximity to the scaphoid were released in an attempt to preserve the palmar capsule and ligaments.[29]

Method for the simulation of 4-CF

The radiolunate and radioscaphoid Kirschner wires were removed, and complete resection of the

FIGURE 3: Fluoroscopic image demonstrating the simulation of a 4-CF. K-wire fixation of the triquetrohamate and capitolunate joints was performed with the addition of a complete scaphoidectomy.

scaphoid was performed. The 4-CF was simulated using 1.6-mm Kirschner wires placed in a retrograde fashion between the bones of the distal and proximal rows to simulate the fusion of the capitolunate and triquetrohamate joints (Fig. 3). Similar techniques have been previously described.[3,30]

Method for the simulation of PRC

The PRC was performed following the removal of the wires and excision of the lunate and triquetrum. Care was taken to avoid iatrogenic injury to the lunate fossa of the distal radius and head of the capitate, thereby preserving the intended postprocedure articulation.[31]

Statistical analysis

Repeated-measure analysis of variance and the Tukey multiple comparison test were performed. Significance was set at $P < .05$. Results were displayed, with letters representing statistically significant differences. Groups not connected by the same letter were determined to be significantly different (ie, a vs b, $P < .05$). As previously described, a post hoc power analysis revealed that 8 cadavers were needed to detect a significant difference in one mean of approximately 5° for ROM and 0.1 MPa for contact pressure.[29] An intraclass correlation coefficient analysis was performed to determine the repeatability (ie, intraobserver) and reproducibility (ie, interobserver) of the wrist-specific goniometer measurements of ROM using a 2-factor analysis of variance.

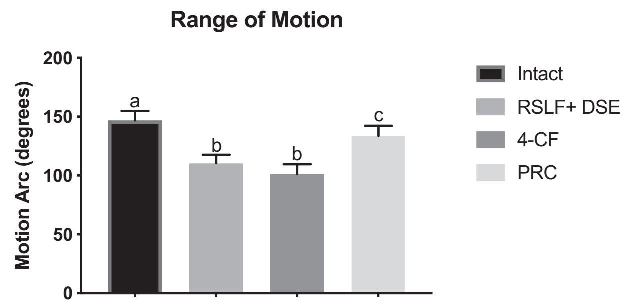

FIGURE 4: ROM of the native cadaveric wrist and simulated surgical groups in the flexion, extension, radial deviation, and ulnar deviation planes. The error bars represent the SD.

RESULTS

The ROM (Fig. 4), contact pressure (Fig. 5), contact area (Fig. 6), and contact force (Fig. 7) were evaluated in the native cadaveric wrist and the 3 simulated-treatment groups. The mean total arc of flexion-extension and radioulnar deviations obtained in the native wrist was 100° and 48°, respectively. A decrease in the wrist arc ROM was observed in the 4-CF and RSLF+DSE simulation groups compared with that in the native wrist (Fig. 4) (mean difference of 46°; 95% CI, 33−59; $P < .05$; and mean difference of 36°; 95% CI, 24−49; $P < .05$, respectively). There was a decrease in the wrist arc ROM in the PRC group compared with that in the native wrist (mean difference of 13°; 95% CI, 0.4−26; $P < .05$). However, the PRC group had a greater wrist arc ROM compared with the 4-CF and RSLF+DSE groups (mean difference of 33°; 95% CI, 19−45; $P < .05$; and mean difference of 23°; 95% CI, 10−36; $P < .05$, respectively), with a greater ulnar deviation than the 4-CF and RSLF+DSE groups (13°; 95% CI, 1−26; $P < .05$; and 17°; 95% CI, 5−29; $P < .05$, respectively) and greater extension than the 4-CF group (mean difference of 15°; 95% CI, 3−28; $P < .05$). There was no significant difference in the wrist arc ROM between the RSLF+DSE and 4-CF groups (mean difference of 9°; 95% CI, −4 to 22; $P = .23$). The intraclass correlation coefficient values for reproducibility in all the groups tested ranged from 0.80 to 0.98, indicating good-to-excellent agreement. The intraclass correlation coefficient values for repeatability ranged from 0.64 to 0.96, indicating moderate-to-excellent agreement.[32]

The pressure analysis demonstrated a statistically significant increase in the carpal pressures compared with the native midcarpal and radiocarpal pressures in the RSLF+DSE, 4-CF, and PRC simulation groups (Fig. 5 and Table 1). Among the 3 simulation groups,

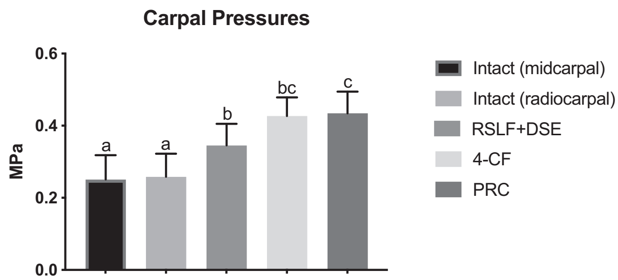

FIGURE 5: Carpal pressures of the native cadaveric wrist and simulated surgical fusion groups. The error bars represent the SD.

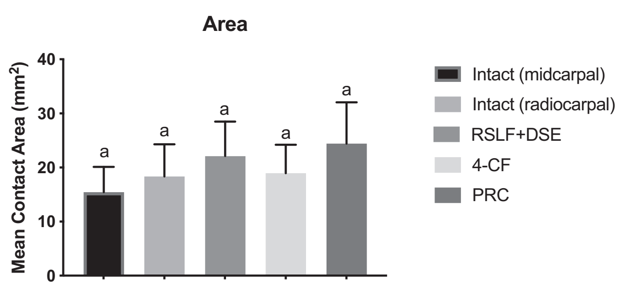

FIGURE 6: Contact areas of the native cadaveric wrist and simulated surgical fusion groups. The error bars represent the SD.

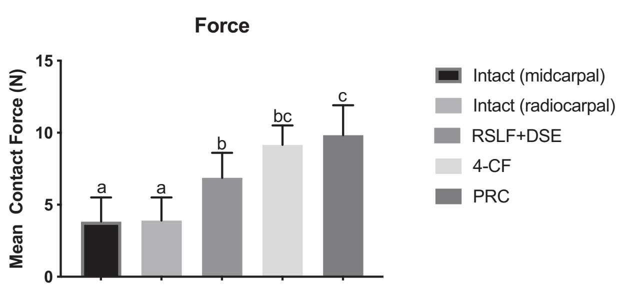

FIGURE 7: Mean contact forces of the native cadaveric wrist and simulated surgical groups. The error bars represent the SD.

the carpal pressures were not significantly different between RSLF+DSE and 4-CF (mean difference of −0.082 MPa; 95% CI, −0.164 to 0.000; $P = .05$), but they had significantly decreased carpal pressures compared with PRC (mean difference of −0.089 MPa; 95% CI, −0.171 to −0.007; $P < .05$). There was no significant difference in the carpal pressures between 4-CF and PRC (mean difference of −0.008; 95% CI, −0.090 to 0.075; $P = .10$).

The mean contact area of the principal articulation was similar among all the treatment groups, ranging from 19.0 mm^2 to 24.4 mm^2, with no statistically significant difference relative to that in the native wrist (Fig. 6). As described, the mean contact force was derived using the total pressure and contact area measurements. The RSLF+DSE, 4-CF, and PRC simulation groups had statistically significant increases in the mean contact force compared with the native wrist (Fig. 7 and Table 2). The RSLF+DSE treatment group had decreased mean contact forces compared with the PRC group (mean difference of −2.96 N; 95% CI, −5.25 to −0.67; $P < .05$) and similar mean contact forces compared with the 4-CF group (mean difference of −2.28 N; 95% CI, −4.58 to 0.01; $P = .05$). There was no significant difference in the mean contact forces between 4-CF and PRC (mean difference of −0.68 N; 95% CI, −2.97 to 1.62; $P = .92$).

DISCUSSION

A comprehensive understanding and comparison of the biomechanical effects of RSLF+DSE, 4-CF, and PRC on the wrist are lacking. This study provides biomechanical data regarding the effect of each technique on wrist carpal forces exhibited at the primary articulation. However, the clinical consequences of the biomechanical findings of each technique remain unclear. Our study demonstrates 3 principal findings that can provide an insight to treating physicians. First, we defined the biomechanics of the native wrist in terms of ROM, carpal contact pressures, carpal contact areas, and carpal contact forces. Furthermore, our study demonstrated how these biomechanical characteristics are altered after RSLF-DSE, 4-CF, and PRC. Finally, our study validated that PRC is motion-conserving but has the greatest contact force, whereas RSLF-DSE and 4-CF may cause a decrease in the ROM but have lower contact forces. Compared with the native wrist, the 4-CF and RSLF-DSE simulation groups had equivalently decreased ROM and increased contact forces, whereas PRC best preserved the ROM but at the expense of significantly increased contact forces.

Several studies have reported favorable outcomes with the use of RSLF+DSE, 4-CF, and PRC. In a retrospective clinical study, Berkhout et al[7] reported no difference in patient-reported outcomes in patients with SLAC and those with other wrist conditions treated with PRC and 4-CF, whereas active ROM was marginally superior in patients treated with PRC. Similarly, Wagner et al[18] found similar ROM results and no difference in long-term functional outcomes when they compared the 2 techniques in patients aged less than 45 years old. In 2 systematic reviews, Mulford et al[6] and Saltzman et al[10] reported an improved overall ROM in patients treated with PRC compared with those treated with 4-CF. Although

TABLE 1. Mean Differences in Contact Pressure (MPa) Between Intact Wrist and Simulated Procedures

Procedures	Mean (95% CI)	*P* value
Intact (midcarpal) versus RSLF+DSE	−0.094 (−0.176 to −0.012)	<.05
Intact (midcarpal) versus 4-CF	−0.176 (−0.258 to −0.094)	<.05
Intact (midcarpal) versus PRC	−0.184 (−0.266 to −0.101)	<.05
Intact (radiocarpal) versus RSLF+DSE	−0.087 (−0.169 to −0.005)	<.05
Intact (radiocarpal) versus 4-CF	−0.169 (−0.251 to −0.087)	<.05
Intact (radiocarpal) versus PRC	−0.176 (−0.258 to −0.094)	<.05
RSLF+DSE versus 4-CF	−0.082 (−0.164 to 0.000)	.05
RSLF+DSE versus PRC	−0.089 (−0.171 to −0.007)	<.05
4-CF versus PRC	−0.008 (−0.090 to 0.075)	.10

TABLE 2. Mean Differences in Contact Force (N) Between Intact Wrist and Simulated Procedures

Procedures	Mean (95% CI)	*P* value
Intact (midcarpal) versus RSLF+DSE	−3.04 (−5.33 to −0.74)	<.05
Intact (midcarpal) versus 4-CF	−5.32 (−7.61 to −3.03)	<.05
Intact (midcarpal) versus PRC	−6.00 (−8.29 to −3.70)	<.05
Intact (radiocarpal) versus RSLF+DSE	−2.96 (−5.25 to −0.67)	<.05
Intact (radiocarpal) versus 4-CF	−5.24 (−7.53 to −2.95)	<.05
Intact (radiocarpal) versus PRC	−5.92 (−8.21 to −3.63)	<.05
RSLF+DSE versus 4-CF	−2.28 (−4.58 to 0.01)	.05
RSLF+DSE versus PRC	−2.96 (−5.25 to −0.67)	<.05
4-CF versus PRC	−0.68 (−2.97 to 1.62)	.92

both 4-CF and PRC are considered motion-preserving options for the treatment of SLAC, our study demonstrated a significant reduction in the wrist ROM when 4-CF was compared with PRC.

Of note, 4-CF has been shown to be associated with postoperative complications related to hardware fixation and nonunion.[6,33] However, several authors have suggested that 4-CF is preferable to PRC because the less constrained nature of PRC may predispose the wrist to forces that can lead to adjacent joint arthritic disease over time.[6,19,21,22,34] Interestingly, our study demonstrated no statistically significant difference in the carpal pressures, contact forces, or contact area between PRC and 4-CF, which may raise a question regarding the validity of this assumption. The similarity in the contact areas may be explained by variations in capitate morphology; a flat capitate is the most common type.[35] Additionally, Wagner et al[18] reported similar 10-year total wrist arthrodesis-free and revision-free intervals for both PRC (84% and 81%, respectively) and 4-CF (88% and 80%, respectively).[18] However, these findings were contradicted by a recent study by van Hernan et al,[36] which reported higher revision rates in patients treated with 4-CF compared with those treated with PRC.

Distal scaphoid pole excision in patients undergoing RSLF+DSE attempts to preserve the midcarpal motion needed to perform activities of daily living.[16,37–39] Distal scaphoid excision may also improve union rates by offloading the RSLF fusion.[8,16] In a retrospective review of 47 patients undergoing RSLF+DSE, Mühldorfer-Fodor et al[40] reported a 100% union rate. In contrast, RSLF fusion alone has been reported to have nonunion rates of up to 25%.[41–43] Nonetheless, Ha et al[44] reported good long-term outcomes in patients treated with RSLF with and without the use of DSE/triquetrectomy. Bain et al[41] also reported the resolution of pain and maintenance of function in patients treated with RSLF+DSE and triquetrectomy. It is worth noting that in studies by Holleran et al[29] and McNary et al,[24] RSLF+DSE exhibited significantly increased carpal forces compared with that of the intact wrist, a finding consistent with that of our study.

The limitations of this study include its small sample size and the heterogeneity of the freshly frozen cadavers. The use of a material testing system for the application of a uniaxial load in the neutral wrist position is a previously described method that minimizes the effect of complex articulations and motions of the wrist.[24] The method employing the use of a pressure-sensitive film is also less reliable than that using electronic sensors, and the reproducible placement of sensors within the articulation of choice may be variable. However, this is a previously described and validated technique for this purpose.[25,26] Although different joints were compared directly, their measurements are important and relevant because the joint tested constituted the principal wrist articulation after each simulated procedure. We did not measure all the possible carpal and midcarpal joints in each simulated-treatment specimen because of pragmatic limitations. We were only able to measure the key articulations thought to have the largest effects on carpal/midcarpal pressure. This may have either underestimated or overestimated some of the differences noted. Moreover, the use of an *ex vivo* cadaveric model may have affected the distribution of forces and contact areas of the wrist. A cadaveric study cannot account for *in vivo* factors that affect clinically observed ROM, contact forces, or contact pressures, such as scarring associated with the healing process or changes seen over time secondary to creep.[45] In addition, decortication of the scaphoid and lunate facets of the radius performed using RSLF+DSE in vivo was not performed in our study because this would have prevented sequential simulation of the 4-CF procedure. Lastly, the total ROM arc was measured in this study after each testing condition for an *in vitro* assessment of functional ROM. Although the measurement of the dart thrower's ROM after each simulated procedure would have been interesting to include, this was not assessed because it would have been particularly difficult to evaluate with the traction weight technique methodology used in this study.[46]

A lack of biomechanical studies and randomized clinical trials limits our understanding of the advantages and shortcomings of RSLF+DSE, 4-CF, and PRC. Our study aimed to further understanding of the biomechanical effects of these procedures and elucidate how native carpal loading is altered with each procedure. In conclusion, our study validates that all the procedures tested decrease the ROM and increase the joint contact forces through the principal articulation. Our study validates that PRC, although the most motion-preserving, results in the greatest contact forces at the wrist; 4-CF and RSFL-DSE demonstrate similar joint forces and ROM. Although our findings provide some insight into the biomechanical consequences of SLAC treatment options, the ultimate clinical decision largely depends on an understanding of each procedure's unique complication profile, patient indications, and the surgeon's comfort with each technique.

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