A commentary by Tennyson Block, MD, is linked to the online version of this article at jbjs.org.

Role of Ligament Stabilizers of the Proximal Carpal Row in Preventing Dorsal Intercalated Segment Instability

A Cadaveric Study

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Background: Isolated injuries of the scapholunate interosseous ligament (SLIL) are insufficient to produce dorsal intercalated segment instability. There is no consensus about which additional ligamentous stabilizers are critical determinants of dorsal intercalated segment instability. The aim of this study was to evaluate the role of the long radiolunate (LRL), scaphotrapeziotrapezoid (STT), and dorsal intercarpal (DIC) ligaments in preventing dorsal intercalated segment instability.

Methods: Thirty fresh-frozen forearms were randomized to 5 ligament section sequences to study the SLIL, LRL, STT, and DIC ligaments. The DIC-lunate insertion (DIC^{L}) and scaphoid insertion (DIC^{S}) were studied separately; the DIC insertions on the trapezium and triquetrum were left intact. Loaded posteroanterior and lateral fluoroscopic images were obtained at baseline and repeated after each ligament was sectioned. After each sequence, the wrists were loaded cyclically (71 N). The radiolunate angle was measured with load. Dorsal intercalated segment instability was defined as an increase of >15° in the radiolunate angle compared with baseline.

Results: Division of the SLIL did not increase the radiolunate angle. Section of the SLIL+LRL or SLIL+DIC^{L} significantly increased the radiolunate angle but did not produce dorsal intercalated segment instability. Section of the SLIL+STT or SLIL+DIC^{L}+DIC^{S} produced dorsal intercalated segment instability.

Conclusions: In order to produce dorsal intercalated segment instability, complete scapholunate injuries require the disruption of at least 1 critical ligament stabilizer of the scaphoid or lunate (the STT or DIC^{L}+DIC^{S}).

Clinical Relevance: When treating SLIL tears with dorsal intercalated segment instability, techniques to evaluate the volar and dorsal critical stabilizers of the proximal carpal row should be considered.

Scapholunate "dissociation" is defined as the "loss of synchronous motion or normal alignment between the scaphoid and the lunate"[1] and is thought to result from disruption of the scapholunate interosseous ligament (SLIL). Associated attenuation or disruption of ≥1 secondary ligamentous stabilizers (Fig. 1) allows the scaphoid to rotate into flexion independent of the lunate (rotatory subluxation of the scaphoid) while the lunate may rotate into extension. This is thought to be initiated by an unopposed extension moment transmitted from the triquetrum through the lunotriquetral interosseous ligament to the lunate. The scaphoid and the distal carpal row translate dorsally, transferring the lunocapitate contact area dorsally on the lunate, further promoting lunate extension[2].

Pathologic extension of the lunate, termed *dorsal intercalated segment instability,* is present when lunate dorsal tilt exceeds 15° with respect to the sagittal long axis of the radius[1,3].

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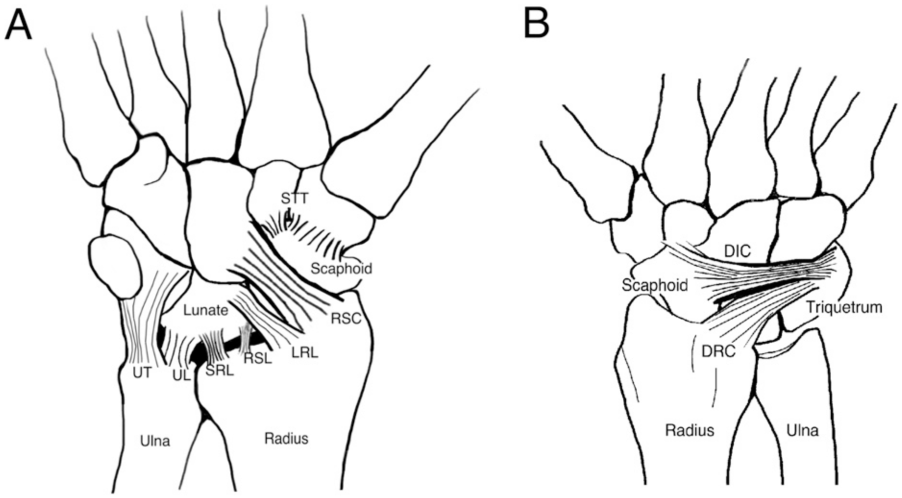

Fig. 1

Figs. 1-A and 1-B Schematic representation of the ligament stabilizers of the scapholunate joint. **Fig. 1-A** Volar view. STT = scaphotrapeziotrapezoid ligament complex, RSC = radioscaphocapitate ligament, LRL = long radiolunate ligament, RSL = radioscapholunate ligament, SRL = short radiolunate ligament, UL = ulnolunate ligament, and UT = lunotriquetral ligament (short radiolunate). **Fig. 1-B** Dorsal view. DIC = dorsal intercarpal ligament and DRC = dorsal radiocarpal ligament.

Isolated SLIL disruption is insufficient to produce dorsal intercalated segment instability[4,5]. Despite nearly 50 years of clinical and mechanical research since the term was coined[6], there is no consensus regarding which secondary ligament stabilizers must be injured or attenuated to cause dorsal intercalated segment instability.

Dorsal lunate tilt has been studied by selectively cutting the dorsal intercarpal ligament (DIC), scaphotrapeziotrapezoid complex (STT), dorsal radiocarpal ligament, and radioscaphocapitate ligament[3,7,8], but dorsal intercalated segment instability has not been consistently produced. In a prior study by Short et al., the lunate significantly extended when both the SLIL and the STT were sectioned, but dorsal intercalated segment instability did not develop[4].

Nagao et al. demonstrated that the DIC originates on the triquetrum and has important insertions on both the scaphoid and the lunate, with a less stout insertion on the trapezium[9]. Still, it is not clear if detaching the DIC from only the scaphoid or only the lunate would produce the same effect, or if detaching only the lunate insertion would be

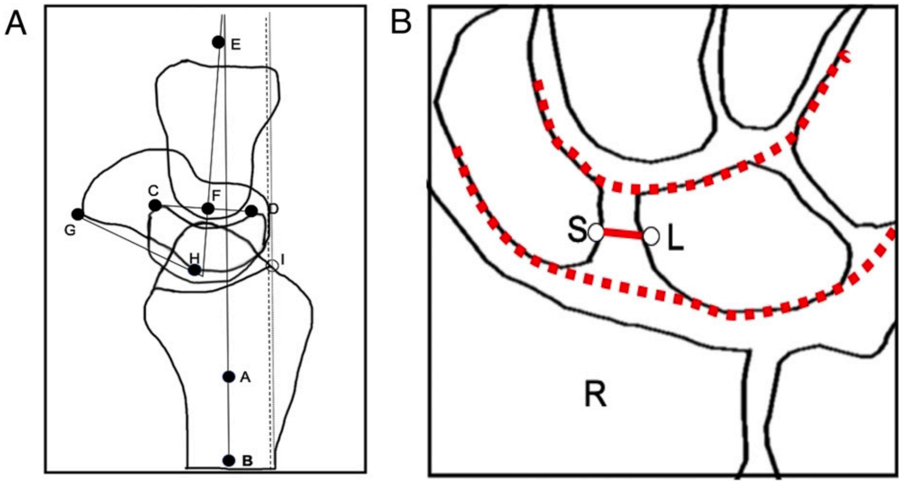

Fig. 2

Fig. 2-A The longitudinal axis of the radius was defined by a bisector at points 2 and 5 cm proximal to the radiocarpal joint. The radiolunate angle[28] is formed by the radial axis (AB) and a line (EF) perpendicular to the tangent of the dorsal and palmar poles of the lunate (CD). The scapholunate angle is formed by a tangent (GH) to the volar surface of the scaphoid and the axis of the lunate (EF). Dorsal scaphoid translation[29] is the distance between a line tangential to the proximal articular surface of the scaphoid (dashed line) and parallel to the longitudinal axis of the radius (AB), and a line drawn through the dorsal scaphoid facet (I) of the distal part of the radius (dotted line). **Fig. 2-B** The scapholunate gap[13] is the distance between the scaphoid (S) and lunate (L) at the midpoints of Gilula's lines (dotted lines) for the proximal carpal row. R = distal part of the radius.

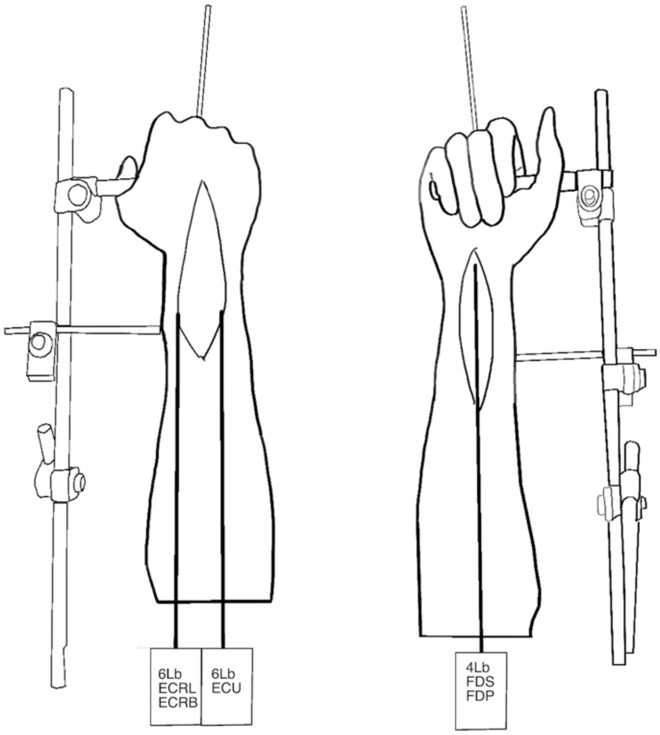

Fig. 3
Forearm mounted in the custom test frame with loads attached. Five-millimeter external fixator pins were introduced into the medullary canals of the radius and ulna. A 5-mm transverse pin secured the forearm in neutral pronation-supination. Additionally, a 2.5-mm Schanz pin was introduced into the medullary canal of the 3rd metacarpal to ensure neutral flexion/extension and radial/ulnar deviation during measurements. Weights were attached to the extensor carpi radialis longus and brevis (ECRL and ECRB) together, extensor carpi ulnaris (ECU), and flexor digitorum superficialis (FDS) and profundus (FDP) together.

enough to produce dorsal intercalated segment instability in the context of complete SLIL disruption[8,10]. The DIC's insertions on all 3 bones of the proximal carpal row make it a strong contender as one of the critical stabilizers of the proximal carpal row.

Recently, the long radiolunate (LRL) ligament has gained attention as a potential critical stabilizer of the lunate[11]. Van Overstraeten and Camus identified a significant association between the severity of SLIL injuries and LRL injuries[12]. Because the DIC and LRL directly insert on the lunate and are oriented in such a direction as to oppose dorsal intercalated segment instability, and because division of the STT ligament complex has been implicated in proximal row instability, we chose these ligaments as the ligaments most likely leading to postural abnormalities of the lunate following division in the SLIL-deficient wrist.

The purpose of our study was to evaluate the impact of sequential section of the SLIL, LRL, STT, and portions of the DIC on lunate extension. We hypothesized that dividing the SLIL is insufficient to cause dorsal intercalated segment instability and that disruption of ≥1 critical ligamentous stabilizers is necessary to produce dorsal intercalated segment instability. We further postulated a differential effect on lunate extension following division of the DIC insertions on the lunate and scaphoid.

Materials and Methods

Specimen Selection

Thirty fresh-frozen cadaveric forearms without radiographic abnormalities were selected for study. Eighteen donors were male, and the mean age at the time of donor death was 50 years (range, 21 to 65 years). Specimens were stored at −20°C and thawed for 18 hours before testing.

Radiographic Measurements

Baseline posteroanterior, lateral, oblique, and loaded clenched-fist posteroanterior and lateral fluoroscopic images[13,14] of the wrist were obtained using a C-arm (Fluoroscan; Hologic). A radiopaque marker was included to adjust for magnification.

One of the specimens (in group 4) appeared normal on radiographs, but capsulotomy revealed a 20% tear of the

TABLE I Donor Characteristics

	Group 1	Group 2	Group 3	Group 4	Group 5	P Value
No.	6	6	6	6	6	
Age* *(yr)*	50.5 ± 13.2	43.3 ± 18.2	46.8 ± 9.3	51.6 ± 9.7	60.6 ± 3.1	0.688†
BMI* *(kg/m²)*	24.3 ± 3.6	22.6 ± 3	25 ± 3.5	24.8 ± 3.5	24.4 ± 7.5	0.681†
Male *(no.)*	3	4	4	4	3	0.912‡
Right side *(no.)*	1	4	2	3	2	0.330‡
Lunate type *(no.)*						0.821‡
I: <2 mm	1	3	2	2	1	
II: >4 mm	3	1	1	2	2	
Intermediate	2	2	3	2	3	

*The values are given as the mean and SD. †One-way ANOVA. ‡Fisher exact test.

TABLE II Baseline Measures

	Mean ± SD (N = 6 per Group)					
	Group 1	Group 2	Group 3	Group 4	Group 5	P Value*
Radiolunate angle *(°)*	4 ± 3.5	0.95 ± 6.5	5.5 ± 10.1	−4.8 ± 3.8	1.5 ± 2.4	0.06
Scapholunate angle *(°)*	54 ± 8	53.1 ± 8	57.4 ± 4.1	55.1 ± 6.4	54.8 ± 6.5	0.736
Scapholunate gap *(mm)*	2 ± 0.4	1.6 ± 0.5	2 ± 0.6	2.1 ± 0.6	1.9 ± 0.5	0.281
Dorsal scaphoid translation *(mm)*	−0.6 ± 0.4	−0.2 ± 0.4	−0.2 ± 1	0.2 ± 0.5	−0.1 ± 0.6	0.21

*One-way ANOVA.

membranous portion of the SLIL. The specimen was not excluded because it had normal radiographic parameters, no signs of cartilage wear, a normal dorsal and palmar SLIL, and no signs of elongation or rupture of other ligaments.

Images were reviewed with Horos, version 2.1.1 (Horos Project). Carpal measurements are described in Figure 2.

The International Wrist Investigators' Workshop (IWIW) defined dorsal intercalated segment instability as a radiolunate angle of >15°[1]. Because of variability in the baseline radiolunate angles, this definition could underestimate (or overestimate) the effect of ligament section on lunate extension. Therefore, we utilized a more stringent definition of dorsal intercalated segment instability; namely, a 15° increase in the radiolunate angle from baseline.

Lunate type was graded as described by Galley et al.[15].

Cadaveric Model of Scapholunate Instability

The forearms were mounted vertically on a test frame by introducing 5-mm external fixator pins into the medullary canals of the radius and ulna. A 5-mm transverse pin secured the forearm in neutral pronation-supination (Fig. 3). Neutral rotation was confirmed fluoroscopically in the anteroposterior view, with articular surfaces of the distal radioulnar joint in perfect profile and the extensor carpi ulnaris sulcus radial to the ulnar styloid.

Physiologic loads were replicated using a validated protocol simulating the clenched-fist position[13,16]. Weights were attached to the flexor and extensor tendons in clusters with use of number-5 Ethibond (Ethicon) or number-2 FiberWire (Arthrex). The weight was 6 lb (27 N) for the extensor carpi radialis longus and brevis together, 6 lb for the extensor carpi ulnaris, and 4 lb (18 N) for the flexor digitorum superficialis and profundus together. A total load of 16 lb (71 N) was selected to simulate physiologic loads of the wrist and finger flexion[17,18].

Ligament Section

The dorsal, proximal, and volar components of the SLIL were divided. The LRL, STT, and DIC were then divided in 5 different sequences.

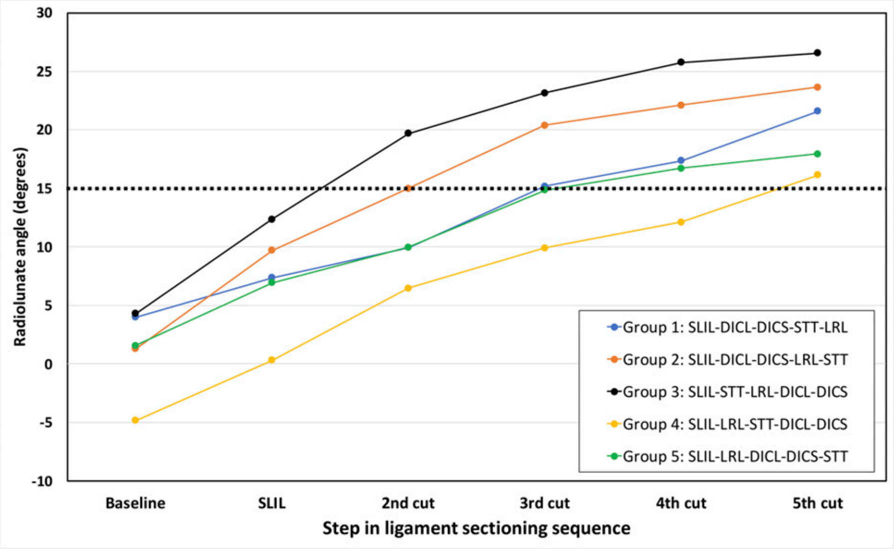

Fig. 4

Mean radiolunate angles. The lines represent the 5 different groups (ligament section sequences), the x coordinate represents each step on the sequence, and the horizontal dotted line represents the IWIW limit for dorsal intercalated segment instability. A detailed graph for each group with significant differences and error bars is presented in Appendix 1.

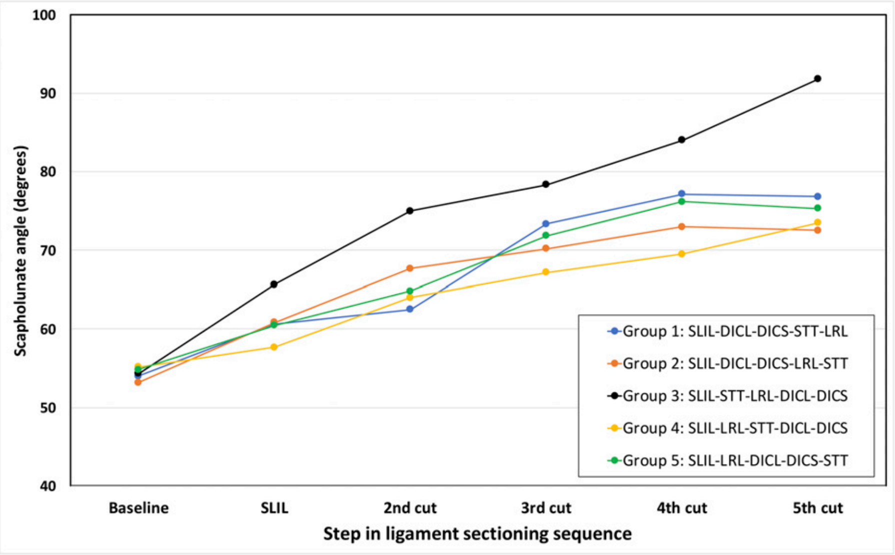

Fig. 5

Mean scapholunate angles. The lines represent the 5 different groups (ligament section sequences). A detailed graph for each group with significant differences and error bars is presented in Appendix 2.

Ligament section was performed using a 2-cm transverse ligament-sparing capsulotomy over the scapholunate interval radial to the dorsal radiocarpal ligament. The SLIL was divided using a number-15 blade and a Hook Knife (Arthrex) to ensure complete division of the most volar and distal segments. To avoid inadvertent section of the LRL insertions on the lunate, the SLIL was divided from the scaphoid.

The DIC was sectioned stepwise using a number-11 blade, detaching its insertions on the lunate (DIC$^{\text{L}}$) from bone. To avoid inadvertent section of the dorsal radiocarpal ligament insertions on the lunate, the blade was introduced with its sharp side oriented distally at the interval between the DIC$^{\text{L}}$ and dorsal radiocarpal ligament, tangential to the dorsal horn of the lunate. When this was done, the dorsal capsule scapholunate septum[19] was also disconnected from the lunate. Next, the attachments of the DIC to the proximal pole and dorsal ridge of the scaphoid (DIC$^{\text{S}}$) were sectioned with a number-11 blade. The triquetral and trapezial insertions of the DIC were left intact.

The LRL was identified through the dorsal approach by flexing the wrist, isolated from the radioscaphocapitate and short radiolunate ligaments using a small Mixter clamp, and sectioned from its radial insertion with a number-11 blade.

The STT ligament was cut through a 1.5-cm transverse incision over the scaphotrapezial joint with a number-11 blade. The flexor carpi radialis tendon was retracted to access the volar side of the STT joint. Complete STT ligament section was confirmed with a Freer elevator and stress maneuvers under fluoroscopy.

The specimens were randomized to 5 groups, with 6 specimens in each group, according to the ligament section sequences: (1) SLIL-DIC$^{\text{L}}$-DIC$^{\text{S}}$-STT-LRL, (2) SLIL-DIC$^{\text{L}}$-DIC$^{\text{S}}$-LRL-STT, (3) SLIL-STT-LRL-DIC$^{\text{L}}$-DIC$^{\text{S}}$, (4) SLIL-LRL-STT-DIC$^{\text{L}}$-DIC$^{\text{S}}$, and (5) SLIL-LRL-DIC$^{\text{L}}$-DIC$^{\text{S}}$-STT. Baseline static-loaded clenched-fist posteroanterior and lateral fluoroscopic views were obtained prior to ligament section. After each step in the sequence, the wrists were loaded (75 manual cycles of flexion-extension and 25 cycles of radial-ulnar deviation, 71 N, 1 Hz) and the fluoroscopic views were repeated. At the conclusion of the experiments, the specimens were dissected to confirm complete section of the studied ligaments. No incomplete ligament divisions were identified.

All surgical procedures and mechanical testing were performed by a fellowship-trained orthopaedic hand surgeon under 3.5× loupe magnification.

Statistical Analysis

Power analysis indicated that a sample size of 4 per group would provide an 80% chance of detecting an increase of 15° in the radiolunate angle (assuming a standard deviation [SD] of 5°) after the second ligament in the sequence was cut, with a 0.05 probability level.

One-way analysis of variance (ANOVA) for repeated measures was used to compare the radiolunate angle, scapholunate angle, scapholunate gap, and dorsal scaphoid translation within groups. The Greenhouse-Geisser correction was used depending on the results of the Mauchly sphericity test. The Bonferroni post-hoc test was used to evaluate differences in the results between the steps of the ligament section sequences. A chi-square test or Fisher exact test was used to compare categorical variables among groups.

Statistical analysis was performed using SPSS Statistics 20.0 software (IBM). Graphs were drawn with Prism 7 (GraphPad). An alpha value of <0.05 was used to determine significance.

Results

No significant differences were found among groups in terms of age, sex, body mass index (BMI), or lunate type (Table I). The radiolunate angle, scapholunate angle, scapholunate gap,

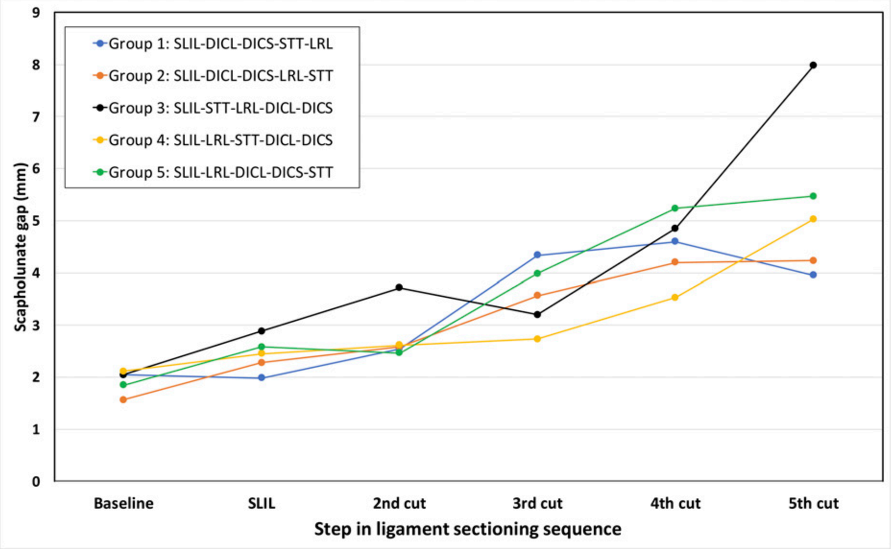

Fig. 6

Mean scapholunate gaps. The lines represent the 5 different groups (ligament section sequences). A detailed graph for each group with significant differences and error bars is presented in Appendix 3.

and dorsal scaphoid translation measurements also did not differ among the 5 groups at baseline (Table II) or after all ligaments were cut.

Radiolunate Angle

None of the groups exhibited a significant increase in the radiolunate angle when only the SLIL was cut (group 1: p = 0.73, group 2: p = 0.53, group 3: p = 0.83, group 4: p = 0.71, and group 5: p = 0.41). However, a significant increase in the radiolunate angle from baseline was observed when, in addition to the SLIL, the DIC^{L} (group 1: p = 0.018, group 2: p = 0.0196), LRL (group 4: p = 0.0017, group 5: p = 0.017), or STT (group 3: p = 0.0113) was cut. The radiolunate angle threshold of 15° for dorsal intercalated segment instability (IWIW criterion) was reached after SLIL-DIC^{L}-DIC^{S} section in group 1, SLIL-DIC^{L} section in group 2, SLIL-STT in group 3, all ligaments in group 4, and SLIL-LRL-DIC^{L} in group 5 ($p < 0.0001$) (Fig. 4).

Using our more stringent second definition for dorsal intercalated segment instability (a 15° change in the radiolunate angle from baseline), dorsal intercalated segment instability was produced after all ligaments were sectioned in group 1,

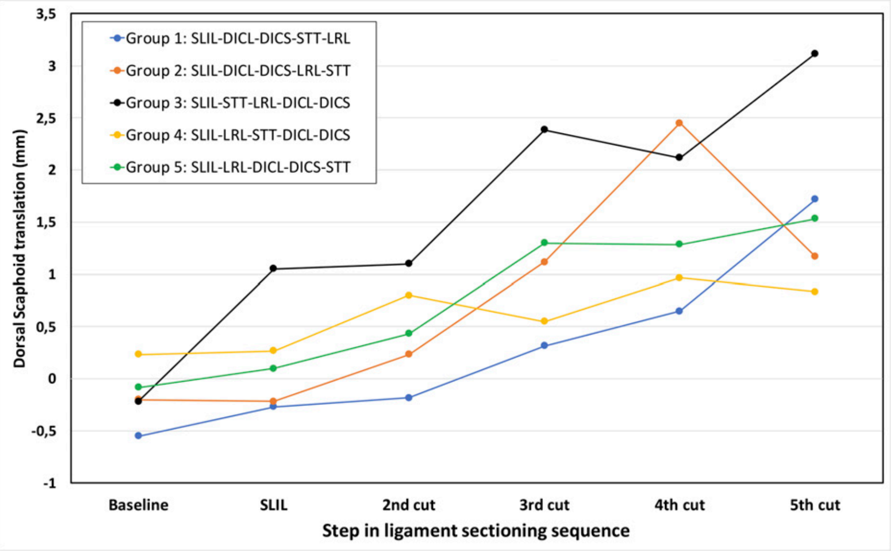

Fig. 7

Mean dorsal scaphoid translation. The lines represent the 5 different groups (ligament section sequences). A detailed graph for each group with significant differences and error bars is presented in Appendix 4.

SLIL-DIC^L-DIC^S in group 2, SLIL-STT in group 3, SLIL-LRL-STT in group 4, and SLIL-LRL-DIC^L-DIC^S in group 5.

Scapholunate Angle

No significant change in the scapholunate angle was found after SLIL section. Significant increases in the scapholunate angle were found after DIC^L section in groups 1 ($p = 0.0235$) and 2 ($p = 0.003$), with a stepwise increase when the DIC^S was cut in group 1 ($p = 0.0019$). A significant increase in the scapholunate angle was demonstrated in group 3 when the STT was cut ($p = 0.0008$) and in group 4 when the LRL+STT were cut ($p = 0.0038$), without significant incremental increases after the DIC^L+DIC^S were cut. Finally, the scapholunate angle significantly increased in group 5 when the LRL+DIC^L were cut, with no additional significant change after section of the DIC^S or STT (Fig. 5).

Scapholunate Gap

Section of the SLIL did not significantly increase the scapholunate gap. A significant change was found after section of the DIC^L+DIC^S+STT in group 1, all ligaments in groups 2 and 3, LRL+STT+DIC^L in group 4, and LRL+DIC^L+DIC^S in group 5 (Fig. 6).

Dorsal Scaphoid Translation

Significant dorsal scaphoid translation was identified only in groups 1 and 3 after all ligaments were sectioned ($p = 0.0078$ and $p = 0.014$, respectively) (Fig. 7).

Discussion

The question of what causes dorsal intercalated segment instability has been studied extensively without consensus. Mitsuyasu et al. found that SLIL division was insufficient to cause dorsal intercalated segment instability and additional release of the DIC from the scaphoid did not increase dorsal tilt of the lunate. However, in their study, when the lunate insertion of the DIC was also cut, lunate extension significantly increased but did not cause dorsal intercalated segment instability[8]. Similarly, Short et al. were unable to produce dorsal intercalated segment instability with secondary ligament divisions[4,7,20].

In our study, complete SLIL disruption did not cause significant changes in any radiographic parameter studied, even after application of physiologic load. We were able to produce dorsal intercalated segment instability (a radiolunate angle increase of >15°) by sectioning the SLIL+DIC^L+DIC^S or SLIL+STT.

Division of the SLIL+LRL significantly increased the radiolunate angle, but it was insufficient to produce dorsal intercalated segment instability. Therefore, the LRL has a stabilizing effect on lunate extension, and potentially in dorsal intercalated segment instability combined with injury to other lunate stabilizers. In a clinical study of 85 arthroscopic cases, Van Overstraeten and Camus found an association between scapholunate instability and LRL injuries. Interestingly, no significant associations with other secondary ligaments (radioscaphocapitate, short radiolunate, STT, or DIC) were identified[12]. Sandow et al. analyzed normal carpal kinematics using computed tomography (CT) and found that the LRL remained isometric during a full range of flexion and extension[11], indicating a stabilizing role of the LRL during wrist motion. Elsaidi et al. did not find a significant increase in lunate extension after all volar extrinsic ligaments (radioscaphocapitate, LRL, short radiolunate, and radioscapholunate ligament) were sectioned following SLIL division. However, section, in addition, of the DIC insertions on the scaphoid and lunate produced dorsal intercalated segment instability[21], raising the question of whether a combination injury to volar and dorsal secondary stabilizers may be necessary to cause dorsal intercalated segment instability.

In our study, the greatest increase in the radiolunate angle was observed following SLIL+STT division. After studying the contribution of the STT to scaphoid stability in the sagittal plane with an intact SLIL, Drewniany et al. proposed that the STT may prevent scapholunate instability by preventing scaphoid flexion[22]. Garcia-Elias et al. found that patients with scaphotrapeziotrapezoid arthritis (with a normal SLIL) treated with resection of the distal fourth of the scaphoid (including the STT insertion) had an average 8° increase in the radiolunate angle[23]. Thus, the STT could be considered not only a critical restraint to scaphoid flexion but also a stabilizer of the proximal row. A postulated mechanism for dorsal intercalated segment instability in our group 3 after SLIL+STT division is that dissociation between the scaphoid and lunate increased the scapholunate angle and the scaphoid translated dorsoradially[24]. This kinematic change resulted in a loss of the normal scapholunate joint reaction force, which allowed the lunate to translate radially and the LRL to slacken.

When the DIC^L was sectioned following SLIL division the radiolunate angle increased significantly, which was enough to produce dorsal intercalated segment instability in some specimens. Subsequent section of the DIC^S increased lunate extension to dorsal intercalated segment instability. Previous anatomic studies of the dorsal ligaments identified a variable DIC insertion on the lunate in 25% to 90% of wrists[25]. Viegas et al. described osseous insertions of the DIC on the scaphoid (in 97% of their cases) and lunate (in 90%) and a relatively constant attachment to the dorsal SLIL[10]. In our study, we identified the DIC attachments to the lunate dorsal pole in all specimens as well as its normal insertion on the scaphoid dorsal ridge.

There was no change in the scapholunate angle, scapholunate gap, or dorsal scaphoid translation when the SLIL was sectioned alone. Subsequent disruption of the DIC^L or STT caused significant increases in the scapholunate angle. As an increase in this angle is a result of scaphoid flexion and/or lunate extension, it highlights the role of volar and dorsal ligament stabilizers on the scapholunate articulation.

In order to produce a significant increase in the scapholunate gap, it was necessary to divide the SLIL+DIC^L+DIC^S and a volar ligament (STT or LRL). This supports a codependence of the dorsal and volar secondary stabilizers on this joint.

A significant increase in dorsal scaphoid translation was identified in only 2 groups after all study ligaments were cut. We found only 1 investigation identifying dorsal scaphoid translation after ligament section, and in that study it increased by

0.2 mm following division of the SLIL, the LRL, and the dorsal aspect of the capsule[5]. Scaphoid dorsal translation in our study could be identified dynamically during video fluoroscopy in wrist flexion with spontaneous relocation in wrist extension after all ligament sections were completed (Video 1). We suspect that static scaphoid dorsal translation is a late finding in scapholunate dissociation and requires loss of additional periscaphoid ligaments, including the dorsal ligament complex. This parameter of scapholunate instability[24,26] requires further investigation.

There are limitations of our study. First, only ligaments with attachments on the lunate (the LRL and DIC)[9] or those known to be important stabilizers of the scapholunate joint (the STT)[22,23] were studied. Second, because of a limited number of specimens, we were not able to test all possible combinations of the evaluated ligaments. It would have been of interest to evaluate the role of the DIC^{S} by sectioning it prior to the DIC^{L}. The number of cycles used in our study (100) followed prior loading protocols[16,27] and was chosen to allow adequate soft-tissue creeping and reach a stable state after each step of the sequence. Protocols of up to 1,000 cycles have been used[13] to simulate secondary stabilizer attenuation following primary intrinsic ligament injury. A final limitation is that measurements were made radiographically; CT may have been able to detect more subtle or 3-dimensional changes in the scapholunate gap and dorsal scaphoid translation. However, since our primary outcome parameter (dorsal intercalated segment instability) is based on radiographic measurements, the use of radiographs is more clinically relevant.

In conclusion, we identified a volar (LRL) and a dorsal (DIC^{L}) critical stabilizer of the lunate that, when divided in association with complete SLIL disruption, significantly increased dorsal lunate tilt. We further demonstrated a dorsal (DIC) and a volar (STT) critical stabilizer of the proximal carpal row that, when divided in association with complete SLIL disruption, produced dorsal intercalated segment instability. Thus, when considering treatment for SLIL rupture, particularly when it is associated with a scapholunate gap and dorsal intercalated segment instability, it may be helpful to utilize high-resolution magnetic resonance imaging (MRI) and/or arthroscopy to better understand the extent of additional ligament injuries and to customize treatment to address the critical stabilizers of the intercalated segment. This information will be useful when considering the varied and novel reconstructive options for scapholunate injuries currently in practice (volar, dorsal, 360°, and combined).

Appendix

eA Supporting material provided by the authors is posted with the online version of this article as a data supplement at jbjs.org (http://links.lww.com/JBJS/F385). ■

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