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Original Research

Dorsal Bone–Ligament–Bone Reconstruction of Chronic Lunotriquetral Instability: Biomechanical Testing

Janina M. Riederer, MD, [*,†] Tom Adler, MD, [*,†,‡] Esther Vögelin, MD, PhD, [*] Luzian Haug, MD [*]

[*] Department of Plastic and Hand Surgery, Inselspital, Bern University Hospital, University of Bern, Switzerland

A R T I C L E I N F O

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Purpose: Lunotriquetral (LT) instability is uncommon and few biomechanical analyses of the condition exist. For chronic LT instabilities, arthrodesis has long been the treatment of choice but has a high risk for nonunion. The aim of this study was to evaluate an alternative treatment option using a bone–ligament–bone graft in a cadaver model and compare it with a conventional arthrodesis.

Methods: We used 10 cadaveric forearms with different loading positions. We employed computed tomography scans to evaluate the LT joint. Scans were performed with the joint intact after we sectioned the dorsal LT ligament and the palmar LT ligament. The joints were then reconstructed using a bone–ligament–bone graft from the capitate–hamate joint as well as with a compression screw simulating arthrodesis. The joints were then rescanned and 3-dimensional analysis was performed using specialized 3-dimensional software.

Results: Sectioning the dorsal part of LT ligament had little effect on kinematics; however, additional division of the palmar LT ligament resulted in increased mobility. Restoration of physiological kinematics could be partially achieved after bone–ligament–bone reconstruction. Arthrodesis showed increased intercarpal motion in the adjacent scapholunate and lunocapitate joints compared with the bone–ligament–bone reconstruction.

Conclusions: The bone–ligament–bone reconstruction displayed physiologic carpal kinematics in the adjacent joints compared with arthrodesis. It provided enough stability but still some mobility in the LT joint to be able to use it as a treatment modality for chronic LT instability without the risk for nonunion. Decreased intercarpal motion was not statistically significant although there appeared to be a trend toward it.

Type of study/level of evidence: Therapeutic IV.

Carpal injuries resulting in instability are a common cause of wrist pain. Although scapholunate injuries are more frequent and thus have received greater attention in the past, lunotriquetral (LT) injuries are not negligible. There is a wide spectrum of injury patterns, which range from stable partial tears to extensive dissociation.[1] Anatomically, the proximal carpal row lacks direct tendon insertions and therefore acts as an intercalated segment, with stability depending mainly on the geometry of the articular surfaces and ligaments.[2,3]

The stabilizing ligaments of the wrist can be divided into extrinsic and intrinsic. The extrinsic ligaments connect the carpals to the radius, ulna, and midcarpus whereas the intrinsic ligaments interconnect 2 carpals. The most important intrinsic ligaments of the proximal carpal row are the scapholunate (SL) and LT ligaments. Like the SL ligament, the LT ligament is *C*-shaped. It is composed of 3 different regions including the dorsal and palmar true ligaments and a proximal membrane. Whereas the SL ligament is strongest dorsally, the LT ligament is the thickest and therefore strongest palmarly.[4]

In the uninjured wrist, the lunate is held in balance by a flexion moment provided by the scaphoid and an extension moment

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Corresponding author: Janina M. Riederer, MD, Department of Plastic and Hand Surgery, Inselspital, Bern University Hospital, University of Bern, Freiburgstrasse 10, 3010 Bern, Switzerland.

E-mail address: jmriederer@gmail.com (J.M. Riederer).

† J.M.R. and T.A. contributed equally to this article.

‡ T.A.'s current address is Orthoklinik Dornach AG, Dornach, Switzerland.

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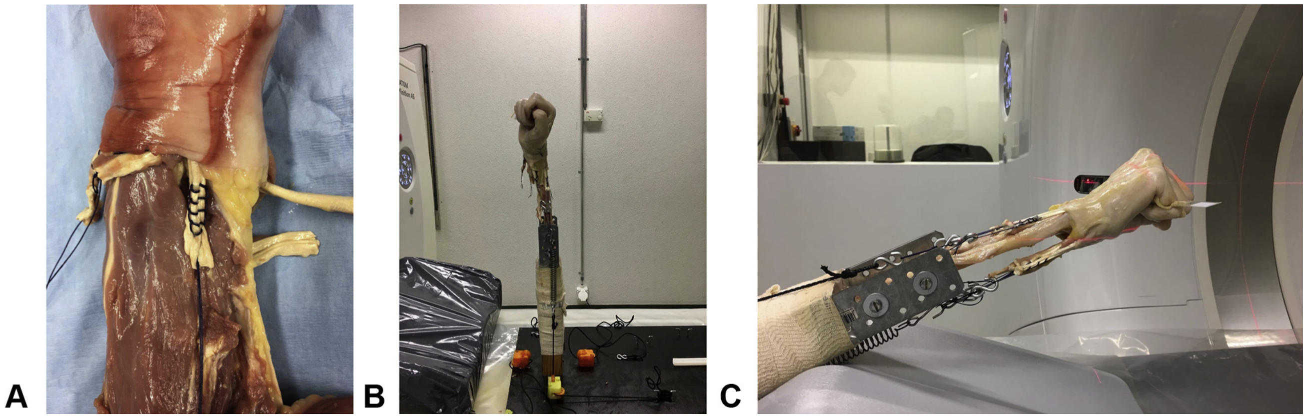

Figure 1. Arming of the tendons and fixation in the test model. **A** Krackow suture technique. **B, C** Fixation in the test model.

provided by the triquetrum, transmitted through the corresponding intrinsic as well as the extrinsic ligaments.[5] With a loss of the integrity of the LT ligament, the triquetrum tends to extend, whereas the lunate, which is still connected to the scaphoid, attempts to flex. Complete rupture of an intrinsic ligament alone does not lead to malalignment in unloaded wrists, because the extrinsic ligaments keep the carpals in position.[6] With additional load on the wrists, however, the motion is greater, forcing the carpals into malalignment as a result of the missing constraint of the intrinsic ligaments. This results in a dynamic instability, seen on dynamic stress views. For static instability, or instability seen on static radiographs, an additional tear or failure of the extrinsic ligaments is necessary.[6]

In the wrist, 2 major instability patterns exist, depending on which carpal ligament is torn. When the proximal and palmar components of the LT ligament fail, the lunate flexes, leading to volar intercalated segment instability.[7] If instead the SL ligaments fail, the scaphoid tends to collapse into an abnormal flexed position, whereas the lunate and triquetrum extend, leading to dorsal intercalated segment instability.[7]

Diagnosis of a dynamic instability is difficult because symptoms such as ulnar-sided wrist pain and loss of grip strength are nonspecific with normal static radiographs.[1] Depending on the chronicity, instability, and anatomy of the wrist, several therapeutic approaches are described in the literature. In acute cases, therapy options include immobilization, arthroscopically assisted stabilization, and direct open LT repair.[8] In chronic cases, treatment options range from arthroscopic debridement[9,10] to LT ligament repair,[8,11] ligament augmentation using either part of the flexor carpi ulnaris (FCU)[8] or extensor carpi ulnaris (ECU)[11,12] or palmaris longus tendon[13] to capsulodesis,[14] arthrodesis,[8,11] ulnar shortening osteotomy,[15] and anterior pr posterior interosseous nerve neurectomy.[16] However, there are no uniform therapy recommendations.

At our institution, we prefer a bone–ligament–bone reconstruction technique using a capitate–hamate bone–ligament–bone graft in patients with chronic LT instability, with promising early clinical results. This reconstruction technique is based on a single dorsal approach for harvesting the graft as well as reconstruction of the LT ligaments with only minimal change to the natural anatomy. Moreover, as observed for the bone–patellar tendon–bone graft for anterior cruciate ligament reconstruction, a bone–ligament–bone graft provides rigid fixation and quicker graft osteointegration than only tendon-in-bone healing using a tendon graft.[17,18]

van Kampen et al[19] introduced a capitate–hamate bone–ligament–bone graft to reconstruct carpal ligament disruptions to treat SL interosseous ligament disruption. Compared with other reported transplants in the literature for SL ligament disruptions, the dorsal capitate–hamate graft was the strongest and therefore the best suited one.[20]

Based on clinical experience and the literature showing altered kinematics and increased strain in adjacent joints after arthrodesis in the ankle and spine,[21,22] we expected our less rigid dorsal bone–ligament–bone reconstruction technique to restore the natural kinematics of the LT joint better and decrease strain on the adjacent joints, thus decreasing the risk for degenerative osteoarthritis compared with an arthrodesis.

In this technique, we decided to reconstruct only the dorsal ligament. Although the palmar ligament is known to be the strongest,[4] we assumed that reconstruction of the dorsal ligament would suffice to restore adequate stability especially as a rotational constraint,[4] because clinical cases at our institution already demonstrated this outcome. This allowed a single dorsal approach to harvest and implant the graft. Consequently, we expected lower morbidity compared with an additional palmar approach by leaving the palmar extrinsic ligaments intact; moreover, it would be easier to perform. Previous studies suggested that palmar extrinsic ligaments are required to maintain joint stability,[23,24] and that scarring of the ligaments may contribute to loss of wrist extension, as reported in a few cases after volar plating of distal radius fractures.[25] Furthermore, in our experience, combined dorsal and volar approaches lead to more stiffness, unless they are performed arthroscopically.

The aim of this study was to assess this reconstruction technique of LT repair biomechanically and compare it with arthrodesis. A secondary aim was to examine the LT ligament by sequential sectioning. According to the results of Ritt et al,[7] only complete sectioning should show a significant change in carpal alignment. We hypothesized that the dorsal bone–ligament–bone reconstruction would restore the natural kinematics of the LT joint and decrease strain on the adjacent joints compared with an arthrodesis.

Materials and Methods

We used 10 Thiel-fixated upper-extremity cadavers provided by the Anatomic Institute of the University of Bern, Bern, Switzerland (7 females and 3 males, aged 78–93 years). We examined all specimens using an x-ray image intensifier to detect anatomic changes that would affect the

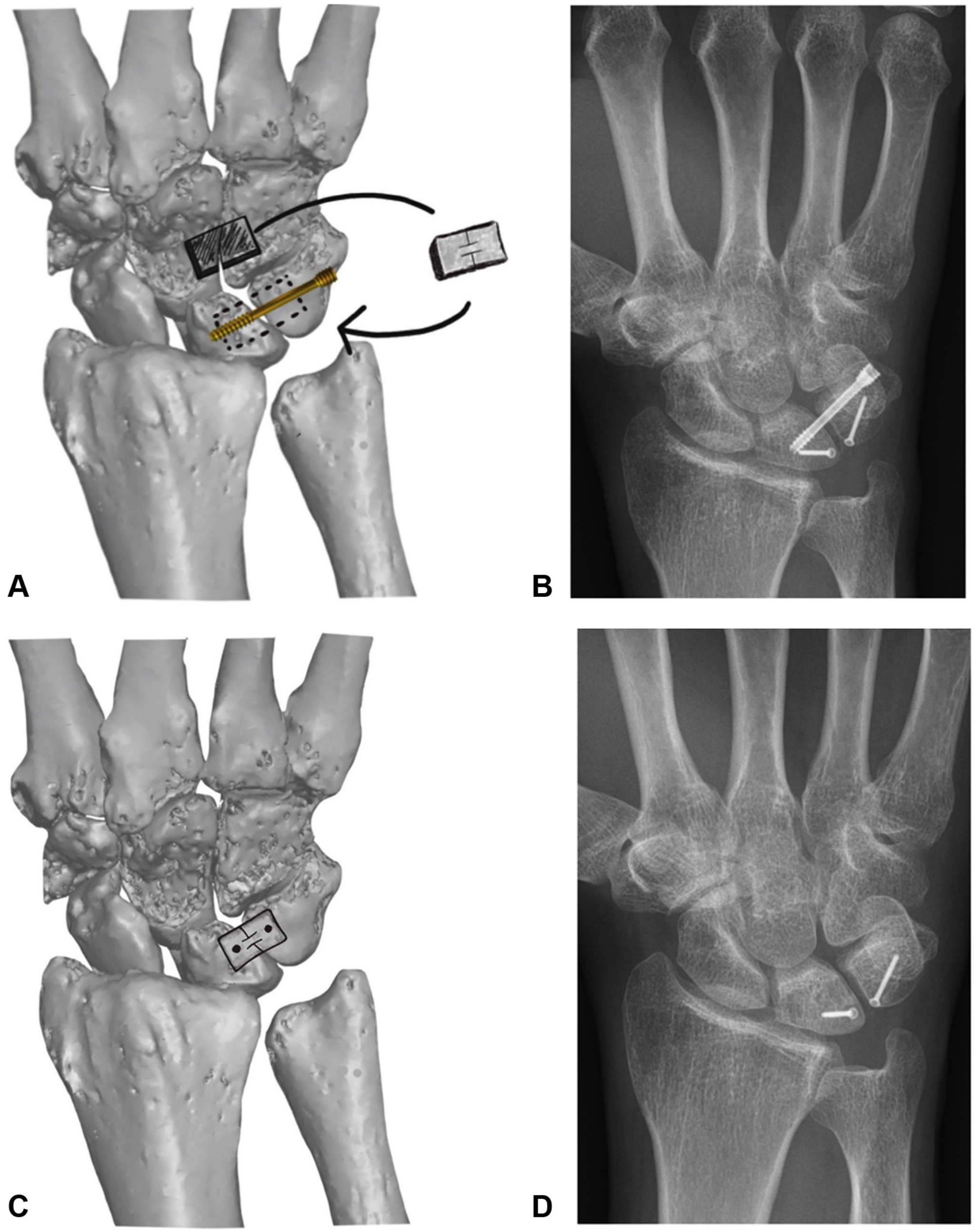

Figure 2. A, B Reconstruction with CCS simulating arthrodesis. **C, D** Reconstruction after removal of CCS.

results, including testing for existing dissociations. Tendons involved in wrist motion and fist closure were identified and dissected. These included the tendons of the extensor carpi radialis longus and brevis (ECRL/B), ECU, flexor carpi radialis (FCR), FCU, flexor digitorum profundus (FDP), and flexor pollicis longus (FPL). We armed the tendons securely with a 1-0 polyglactin 910 thread using the Krackow suture technique[26] (Fig. 1A). The tendons of the ECRL and ECRB were attached together, as well as the tendons of the FDP and FPL. We then fixated the forearms in neutral rotation with 2 screws running through the proximal end of the radial and ulnar bone (Fig. 1B, C).

We performed computed tomography in 5 different wrist positions including flexion, extension, fist closure, radial deviation, and ulnar deviation. For each position, we attached calibrated tension springs to the corresponding tendons with a predefined tension of 50 N; the tension was chosen based on the study of Pollock et al.[27]

For wrist flexion, the spring was attached to the tendons of the FCU and FCR; for extension, ECRL/B and ECU; for radial deviation, ECRL/B and FCR; and for ulnar deviation, FCU and ECU. To simulate fist closure, the FDP, FPL, and ECRL/B and ECU tendons were all attached and loaded.[27]

In total, the protocol was repeated 5 times (5 series, 0–4) for each wrist. The first series of computed tomography tests was conducted in the native state (0) before surgery.

For the second series (1), we approached the LT ligament through a longitudinal incision, partially dividing the extensor retinaculum distally between the fourth and fifth tendon compartments and performed an arthrotomy exposing the intact intercarpal ligaments.

Figure 3. The x axis shows pronation-supination; the y axis, flexion-extension; and the z axis, ulnar-radial deviation. (From CASPA, Balgrist CARD AG.)

We then sectioned the dorsal and proximal part of the LT ligament with a scalpel under visual control, leaving the palmar portion of the ligament as well as the dorsal radiotriquetral ligament intact. Because of the limited number of cadaveric specimens, and so as not to open and manipulate the joint from the palmar side, we decided to perform only a sequential sectioning rather than divide the specimens into 2 groups and compare sectioning of the palmar part with sectioning of the dorsal part.

For the third series (2), we also sectioned the palmar portion, simulating total disruption of the LT ligament.

For the fourth series (3), we incised the extensor retinaculum over the fourth tendon compartment and performed an arthrotomy according to Berger et al,[28] exposing the already cut LT ligament. The capitate–hamate joint and ligament were identified distally to the dorsal intercarpal ligament, and borders of the resection were marked, preserving at least 50% of the ligament to ensure normal kinematics in the capitate–hamate joint.

Through an ulnar incision, we inserted a cannulated compression screw (CCS) (APTUS 3.0, Medartis, Switzerland), stabilizing the LT joint under direct visual as well as fluoroscopy control to align the LT joint correctly.

After that procedure, we harvested the bone–ligament–bone graft of the capitate–hamate joint, similar to the technique described by Weiss.[29] A corresponding bone window of approximately 4 × 4 × 4 mm was removed with a chisel from the dorsal ridge of both the lunate and triquetrum, and the bone–ligament–bone graft was fitted in. After insertion, the graft was fixed using 2 1.2-mm screws (APTUS 1.2 cortical screw) (Fig. 2A, B). To withstand biomechanical testing, we also attached the bone–ligament–bone graft to the lunate and triquetrum with a cerclage using 1-0 polyglactin 910 suture, simulating consolidation. This was performed without disrupting additional structures or strengthening the ligament. To leave the dorsal extrinsic ligaments intact, we did not perform a capsule repair.

For the last series (4), we removed the CCS and tested the reconstruction on its own (Fig. 2C, D).

After testing was completed on all 10 specimens, the CT images were reconstructed into 3-dimensional models using OsiriX Lite software (OsiriX Foundation, Geneva, Switzerland). Using the software Meshmixer (Autodesk, Inc. San Rafael, CA), the 3-dimensional reconstructions of the examined hand could be further separated into single carpals. The specialized 3-dimensional software CASPA (Balgrist CARD AG, Zurich, Switzerland) then calculated relative movements of the carpals compared with the normal wrist after each step (Fig. 3). Intercarpal motion was calculated by subtracting differences in change among different carpals (SL, LT, and lunocapitate [LC]) using statistical software (IBM SPSS Statistics, IBM Corporation, Armonk, NY).

Statistical methods

Data are presented as means (SD). Differences between series were calculated using *t* test; $P < .05$ indicated statistical significance.

Results

Carpal motion relative to intact state

Calculation of the change in angle of individual carpals relative to the intact state resulted in a variety of results, depending on the position of the wrist (Tables 1–3).

Arthrodesis compared with reconstruction

Compared with arthrodesis, the bone–ligament–bone reconstruction showed statistically significant changes: the triquetrum showed a significant change only in the extended position, with less supination and more extension. The lunate showed significant changes in flexion, extension, radial deviation, and ulnar deviation. However, the direction of movement differed depending on the position of the wrist (Table 4).

Intercarpal motion of SL, LC, and LT joints

After arthrodesis, intercarpal motion in the SL and LC joints was significantly increased in the extended and flexed position of the wrist compared with the bone–ligament–bone reconstruction. Removing the CCS, and thus testing the bone–ligament–bone reconstruction alone, partially restored natural kinematics in the adjacent joints; intercarpal motion approximated the value 0, corresponding to intercarpal motion in the native state (Table 5, Fig. 4).

For the LT joint, sectioning of the entire LT ligament led to increased intercarpal motion in flexion and extension. In the extended wrist position, the triquetrum had a greater change in extension than did the lunate. In the flexed wrist position, the triquetrum flexed more than did the lunate. After bone–ligament–bone reconstruction, intercarpal motion in the LT joint decreased, but not statistically significantly (Table 5, Fig. 4).

Table 1
Mean Carpal Motion Relative to Intact State*

Series	x	y	z	x	y	z
	Wrist Extension			Wrist Flexion		
Lunate						
Cut dorsal	Supination −0.3 (0.7)	Extension −**2.4 (1.1)**	Ulnar deviation **1.5 (1.7)**	Supination −0.3 (1.4)	0.0 (2.2)	Radial deviation −0.7 (1.3)
Cut palmar	Supination −**1.3 (1.1)**	Extension −**2.2 (1.5)**	Ulnar deviation 0.1 (1.6)	0.0 (1.6)	Flexion 0.4 (1.7)	Radial deviation −0.2 (1.7)
CCS	Supination −1.7 (3.0)	Extension −**2.1 (2.4)**	Ulnar deviation **2.6 (2.0)**	Supination −**4.8 (2.7)**	Flexion **8.7 (6.7)**	Ulnar deviation **8.1 (4.4)**
BLB graft	Supination −**3.0 (1.9)**	Extension −**3 (3)**	Ulnar deviation **1.1 (1.3)**	Supination −5.3 (3.9)	Flexion **4.1 (5.2)**	Ulnar deviation 2.3 (3.5)
Triquetrum						
Cut dorsal	Supination −0.1 (1.0)	Extension −**2.7 (1.5)**	Ulnar deviation 1.6 (2.7)	Supination −0.6 (1.5)	0.0 (2.7)	Ulnar deviation 0.1 (1.6)
Cut palmar	Pronation **1.3 (1.3)**	Extension −**4.2 (2.5)**	Ulnar deviation 0.2 (2.5)	Supination −0.9 (1.4)	Flexion **1.8 (1.0)**	Ulnar deviation 0.1 (0.7)
CCS	Supination −**4.3 (2.8)**	Extension −0.5 (7.6)	Ulnar deviation 1.5 (5.3)	Supination −4.1 (6.3)	Flexion 3.0 (4.9)	Ulnar deviation **4.9 (4.5)**
BLB graft	Supination −1.5 (2.8)	Extension −**4.6 (4.8)**	Radial deviation −0.2 (4.0)	Supination −5.8 (3.2)	Flexion **4.9 (5.4)**	Ulnar deviation 3.8 (5.6)
	Ulnar Deviation			Radial Deviation		
Lunate						
Cut dorsal	0.0 (1.0)	Extension −0.9 (2.4)	Radial deviation −0.2 (2.0)	Supination −0.2 (2.0)	Flexion 0.5 (1.7)	Radial deviation −0.1 (0.6)
Cut palmar	Supination −0.8 (3.2)	Extension −**3.1 (3.7)**	Radial deviation −**3.3 (2.7)**	Supination −1.0 (1.7)	Flexion 0.4 (3.5)	Radial deviation −0.4 (2.7)
CCS	Supination −**4.7 (3.5)**	Extension −1.9 (5.2)	Ulnar deviation 2.3 (6.2)	Pronation 0.8 (2.4)	Extension −2.0 (4.7)	Radial deviation −2.0 (2.9)
BLB graft	Supination −**3.0 (3.6)**	Extension −**4.1 (5.5)**	Radial deviation −**3.7 (4.6)**	Supination −**1.8 (2.3)**	Extension −1.5 (4.3)	Radial deviation −0.1 (1.7)
Triquetrum						
Cut dorsal	Supination −0.4 (1.9)	Extension −3.0 (5.1)	Radial deviation −0.7 (2.7)	Pronation 0.4 (1.0)	Flexion 0.1 (2.4)	Ulnar deviation 0.3 (1.4)
Cut palmar	Pronation **1.5 (1.4)**	Extension −**4.6 (4.6)**	Radial deviation −**2.5 (2.7)**	Pronation **1.1 (1.5)**	Extension −0.4 (2.9)	Radial deviation −**0.8 (1.2)**
CCS	Supination −3.0 (6.3)	Extension −5.2 (11.6)	Radial deviation −1.2 (6.2)	Supination −**2.7 (3.0)**	Extension −2.5 (4.3)	Radial deviation −0.6 (3.3)
BLB graft	Supination −0.9 (6.5)	Extension −5.8 (10.4)	Radial deviation −3.0 (5.2)	Supination −**2.5 (2.6)**	Extension −2.4 (3.9)	Radial deviation −**2.3 (2.1)**
	Fist					
Lunate						
Cut dorsal	Pronation 0.7 (1.3)	Flexion **6.1 (8.4)**	Radial deviation −**1.3 (1.7)**			
Cut palmar	Supination −0.6 (1.4)	Extension −1.0 (7.9)	Radial deviation −1.0 (2.1)			
CCS	Supination −0.6 (3.0)	Flexion 1.9 (7.1)	Ulnar deviation 1.5 (3.3)			
BLB graft	Supination −**2.1 (2.7)**	Extension −0.4 (7.9)	Radial deviation −**1.7 (1.5)**			
Triquetrum						
Cut dorsal	Pronation 0.2 (1.4)	Flexion 4.6 (7.3)	Radial deviation −**2.1 (2.5)**			
Cut palmar	Supination −0.1 (1.5)	Extension −2.0 (7.2)	Radial deviation −1.5 (3.1)			
CCS	Supination −**3.1 (4.2)**	Extension −1.0 (7.5)	Radial deviation −2.2 (3.7)			
BLB graft	Supination −1.7 (3.1)	Extension −3.1 (9.0)	Radial deviation −**3.5 (3.3)**			

* Data are shown in degrees as mean (SD). Bold numbers indicate statistically significant differences compared with the intact state. Results are displayed in 3 planes (x axis, pronation-supination; y axis, flexion-extension; and z axis, ulnar-radial deviation).

Table 2
Carpal Motion Relative to Intact State in Wrist Extension and Flexion*

Series	Wrist Extension				Wrist Flexion			
	x	y	z	Rotation	x	y	z	Rotation
Scaphoid								
Cut dorsal	−0.6 (0.9)	**−2.4 (1.2)**	**2.2 (1.9)**	**3.7 (1.7)**	−0.5 (1.0)	0.5 (3.0)	−0.3 (1.1)	**2.4 (2.3)**
Cut palmar	−0.3 (1.2)	**−2.4 (2.6)**	1.1 (1.7)	**3.9 (1.4)**	−0.4 (0.9)	**2.2 (1.4)**	−0.1 (1.2)	**2.8 (1.1)**
CCS	−1.3 (2.0)	−0.3 (4.1)	0.6 (3.5)	**5.0 (2.8)**	**−3.6 (2.2)**	**4.2 (2.6)**	**1.8 (1.7)**	**6.4 (2.4)**
BLB graft	**−2.5 (2.5)**	**−3.1 (2.5)**	0.1 (2.5)	**5.3 (2.3)**	**−2.9 (2.1)**	2.3 (4.8)	0.9 (1.9)	**6.1 (2.2)**
Lunate								
Cut dorsal	−0.3 (0.7)	**−2.4 (1.1)**	**1.5 (1.7)**	**3.2 (1.6)**	−0.3 (1.4)	0.0 (2.2)	−0.7 (1.3)	**2.0 (2.1)**
Cut palmar	**−1.3 (1.1)**	**−2.2 (1.5)**	0.1 (1.6)	**3.0 (1.8)**	0.0 (1.6)	0.4 (1.7)	−0.2 (1.7)	**2.3 (1.6)**
CCS	−1.7 (3.0)	**−2.1 (2.4)**	**2.6 (2.0)**	**5.3 (1.9)**	**−4.8 (2.7)**	**8.7 (6.7)**	**8.1 (4.4)**	**13.2 (7.0)**
BLB graft	**−3.0 (1.9)**	**−3.0 (2.7)**	**1.1 (1.3)**	**5.1 (2.4)**	**−5.3 (3.9)**	**4.1 (5.2)**	2.3 (3.5)	**8.6 (4.9)**
Triquetrum								
Cut dorsal	−0.1 (1.0)	**−2.7(1.5)**	1.6 (2.7)	**4.0 (1.9)**	−0.6 (1.5)	0.0 (2.7)	0.1 (1.6)	**2.4 (2.4)**
Cut palmar	**1.3 (1.3)**	**−4.2 (2.5)**	0.2 (2.5)	**5.3 (2.1)**	−0.9 (1.4)	**1.8 (1.0)**	0.1 (0.7)	**2.5 (1.3)**
CCS	**−4.3 (2.8)**	−0.5 (7.6)	1.5 (5.3)	**9.6 (4.1)**	−4.1 (6.3)	3.0 (4.9)	**4.9 (4.5)**	**9.6 (5.4)**
BLB graft	−1.5 (2.8)	**−4.6 (4.8)**	−0.2 (4.0)	**7.6 (3.1)**	**−5.8 (3.2)**	**4.9 (5.4)**	3.8 (5.6)	**10.1 (5.5)**
Capitate								
Cut dorsal	**−2.0 (2.1)**	−1.4 (3.0)	**5.4 (5.5)**	**7.9 (3.8)**	−1.2 (2.5)	0.4 (5.6)	−0.1 (1.8)	**4.1 (4.9)**
Cut palmar	0.2 (1.5)	**−3.1 (2.7)**	1.8 (5.2)	**6.3 (2.6)**	−0.4 (1.1)	**2.6 (2.2)**	0.4 (1.2)	**3.3 (1.8)**
CCS	**−2.7 (1.5)**	0.5 (4.0)	1.6 (5.7)	**7.0 (2.8)**	**−6.1 (2.8)**	**6.1 (3.8)**	**2.4 (3.1)**	**9.5 (4.2)**
BLB graft	0.0 (4.8)	**−5.0 (1.5)**	1.9 (6.8)	**8.4 (4.6)**	**−3.7 (2.6)**	4.0 (6.8)	**2.4 (2.6)**	**8.7 (3.6)**
MC3								
Cut dorsal	**−2.1 (2.2)**	−1.5 (3.3)	**6.3 (6.3)**	**9.0 (4.1)**	−1.7 (3.6)	0.2 (6.8)	−0.3 (2.7)	**4.9 (6.3)**
Cut palmar	−0.2 (1.6)	**−4.0 (2.4)**	2.0 (6.1)	**7.2 (3.3)**	−0.5 (1.5)	**2.8 (2.7)**	0.8 (1.3)	**3.7 (2.3)**
CCS	**−2.6 (1.7)**	0.5 (4.3)	2.2 (6.6)	**7.8 (3.3)**	**−5.7 (2.7)**	**4.4 (4.1)**	**2.1 (2.4)**	**8.2 (3.7)**
BLB graft	**−1.5 (1.8)**	**−4.8 (1.7)**	0.5 (6.7)	**7.9 (3.4)**	**−3.3 (2.6)**	1.1 (7.5)	**1.7 (2.1)**	**7.9 (3.6)**

* Data are shown in degrees as mean (SD). Bold numbers indicate statistically significant differences compared with the intact state. For the x axes, positive values indicate pronation and negative values, supination. For the y axes, positive values indicate flexion and negative values, extension. For the z axes, positive values indicate ulnar deviation and negative values, radial deviation.

Table 3
Carpal Motion Relative to Intact State in Ulnar and Radial Deviation*

Series	Ulnar Deviation				Radial Deviation			
	x	y	z	Rotation	x	y	z	Rotation
Scaphoid								
Cut dorsal	0.7 (1.1)	−1.6 (4.4)	0.0 (1.8)	**4.2 (2.8)**	0.1 (1.4)	0.2 (4.3)	0.0 (1.3)	**3.7 (2.7)**
Cut palmar	**1.6 (1.3)**	**−6.2 (4.7)**	**−1.3 (1.6)**	**6.8 (4.8)**	−0.3 (1.1)	−0.4 (4.4)	−0.2 (1.0)	**3.8 (2.4)**
CCS	−0.1 (3.8)	−5.3 (11.3)	−1.1 (3.8)	**10.9 (7.5)**	0.5 (1.2)	**−2.9 (3.7)**	−0.9 (1.7)	**3.9 (3.5)**
BLB graft	1.5 (3.4)	−8.5 (12.4)	−1.1 (3.5)	**14.7 (4.7)**	**−1.3 (1.5)**	−2.2 (4.9)	−1.2 (1.9)	**5.7 (1.6)**
Lunate								
Cut dorsal	0.0 (1.0)	−0.9 (2.4)	−0.2 (2.0)	**2.7 (2.0)**	−0.2 (1.3)	0.5 (1.7)	−0.1 (0.6)	**2.0 (1.0)**
Cut palmar	−0.8 (3.2)	**−3.1 (3.7)**	**−3.3 (2.7)**	**5.2 (4.8)**	−1.0 (1.7)	0.4 (3.5)	−0.4 (2.7)	**3.8 (2.7)**
CCS	**−4.7 (3.5)**	−1.9 (5.2)	2.3 (6.2)	**8.7 (5.0)**	0.8 (2.4)	−2.0 (4.7)	−2.0 (2.9)	**5.4 (3.6)**
BLB graft	**−3.0 (3.6)**	**−4.1 (5.5)**	**−3.7 (4.6)**	**8.9 (4.3)**	**−1.8 (2.3)**	−1.5 (4.3)	−0.1 (1.7)	**5.1 (2.1)**
Triquetrum								
Cut dorsal	−0.4 (1.9)	−3.0 (5.1)	−0.7 (2.7)	**5.2 (4.1)**	0.4 (1.0)	0.1 (2.4)	0.3 (1.4)	**2.6 (1.2)**
Cut palmar	**1.5 (1.4)**	**−4.6 (4.6)**	**−2.5 (2.7)**	**6.0 (4.9)**	**1.1 (1.5)**	−0.4 (2.9)	**−0.8 (1.2)**	**3.1 (1.9)**
CCS	−3.0 (6.3)	−5.2 (11.6)	−1.2 (6.2)	**12.9 (7.9)**	**−2.7 (3.0)**	−2.5 (4.3)	−0.6 (3.3)	**6.1 (3.7)**
BLB graft	−0.9 (6.5)	−5.8 (10.4)	−3.0 (5.2)	**12.9 (5.8)**	**−2.5 (2.6)**	−2.4 (3.9)	**−2.3 (2.1)**	**5.9 (2.5)**
Capitate								
Cut dorsal	−0.1 (1.9)	−2.2 (4.8)	0.4 (2.2)	**5.1 (2.8)**	0.1 (1.1)	0.3 (4.0)	0.6 (1.5)	**3.7 (2.2)**
Cut palmar	**1.9 (1.7)**	**−7.1 (5.0)**	−1.3 (2.1)	**7.8 (5.3)**	0.5 (1.2)	−0.5 (4.7)	−0.1 (1.2)	**4.3 (2.4)**
CCS	−1.7 (4.6)	−3.4 (11.7)	0.1 (4.3)	**11.6 (6.4)**	−0.3 (1.1)	**−2.9 (3.1)**	0.4 (2.2)	**4.0 (2.8)**
BLB graft	0.0 (4.6)	−6.9 (13.3)	−0.2 (4.1)	**14.5 (5.9)**	**−1.5 (1.5)**	−1.9 (5.0)	−0.8 (2.3)	**5.6 (2.3)**
MC3								
Cut dorsal	0.4 (1.6)	−1.8 (4.9)	0.7 (2.3)	**5.0 (2.9)**	−0.1 (1.3)	0.7 (3.7)	0.6 (1.3)	**3.6 (1.9)**
Cut palmar	**2.0 (1.7)**	**−7.1 (5.0)**	−1.0 (1.8)	**7.7 (5.2)**	0.3 (0.9)	−0.4 (4.7)	−0.1 (1.4)	**4.1 (2.6)**
CCS	−1.1 (4.4)	−3.3 (11.5)	0.4 (3.9)	**11.2 (6.3)**	−0.3 (1.0)	**−2.9 (2.6)**	0.0 (1.5)	**3.6 (2.1)**
BLB graft	0.6 (4.3)	−7.2 (13.5)	0.2 (3.6)	**14.5 (6.0)**	**−1.3 (1.5)**	−1.8 (5.0)	−0.5 (1.9)	**5.1 (2.7)**

* Data are shown in degrees as mean (SD). Bold numbers indicate statistically significant differences compared with the intact state. For the x axes, positive values indicate pronation and negative values supination. For the y axes, positive values indicate flexion and negative values extension. For the z axes, positive values indicate ulnar deviation and negative values, radial deviation.

Table 4
Mean Difference From Arthrodesis to Bone−Ligament−Bone Reconstruction*

Wrist Position	From Arthrodesis to Reconstruction	Mean Difference	*P* Value
Extension			
Lunate	No statistically significant difference		
Triquetrum	Less supination	x: +2.77°	.04
	More extension	y: −4.17°	.02
Flexion			
Lunate	Less flexion	y: −4.61°	.006
	Less ulnar deviation	z: −5.8°	.00002
Triquetrum	No statistically significant difference		
Fist			
Lunate	More supination	x: −1.47°	.03
	More radial deviation	z: −3.16°	.01
Triquetrum	No statistically significant difference		
Radial deviation			
Lunate	Supination	x: −2.55°	.005
	Less radial deviation	z: +1.89°	.011
Triquetrum	No statistically significant difference		
Ulnar deviation			
Lunate	Less supination	x: +1.7°	.002
	Radial deviation	z: −5.99°	.009
Triquetrum	No statistically significant difference		

* X axis, pronation-supination; y axis, flexion-extension; z axis, ulnar-radial deviation.

Discussion

For LT instability, there is no general agreement regarding a treatment technique. Treatment options range from conservative therapy in more acute cases to surgical therapy including arthroscopic debridement, LT ligament repair, ligament augmentation, arthrodesis, ulnar shortening osteotomy, and anteroposterior interosseous neurectomy.[8−16]

For SL ligament reconstruction Nakamura et al[30] report excellent clinical and radiographic results using a capitohamate bone−ligament−bone graft for SL instability and static SL dissociation.[30] Long-term results of van Kampen et al[19] using a capitohamate bone−ligament−bone autograft for SL reconstruction showed results comparable to other SL reconstructive options with no superiority to other techniques. At our institution, the technique of van Kampen et al was transferred to stabilize chronic unstable LT joints, although we recognized that the most stable part of the LT ligament is the palmar part with promising results, indicating possible advantages compared with an arthrodesis or other options. However, because the reconstruction was nonanatomic, we conducted the study for further evaluation.

To our knowledge, to date, there has been no biomechanical assessment of a bone−ligament−bone reconstruction technique for LT repair. The use of a bone−ligament−bone graft to restore carpal

Table 5
Intercarpal Motion: Comparison of Arthrodesis Simulation Versus Bone–Ligament–Bone Reconstruction in SL and LC Joints and Fully Sectioned LT Ligament Versus Bone–Ligament–Bone Reconstruction in LT Joint

Wrist Position	Arthrodesis With CCS	BLB Reconstruction	Difference	*P* Value
SL				
Flexion	−4.5°	−1.8°	2.7°	.015
Extension	1.8°	−0.1°	−1.8°	.048
LC				
Flexion	2.6°	0.1°	−2.5°	.066
Extension	−2.5°	2.0°	4.5°	.002
Sectioning LT ligament				
LT				
Flexion	−1.7°	−.08°	−0.9°	.464
Extension	2.0°	1.6°	0.4°	.771

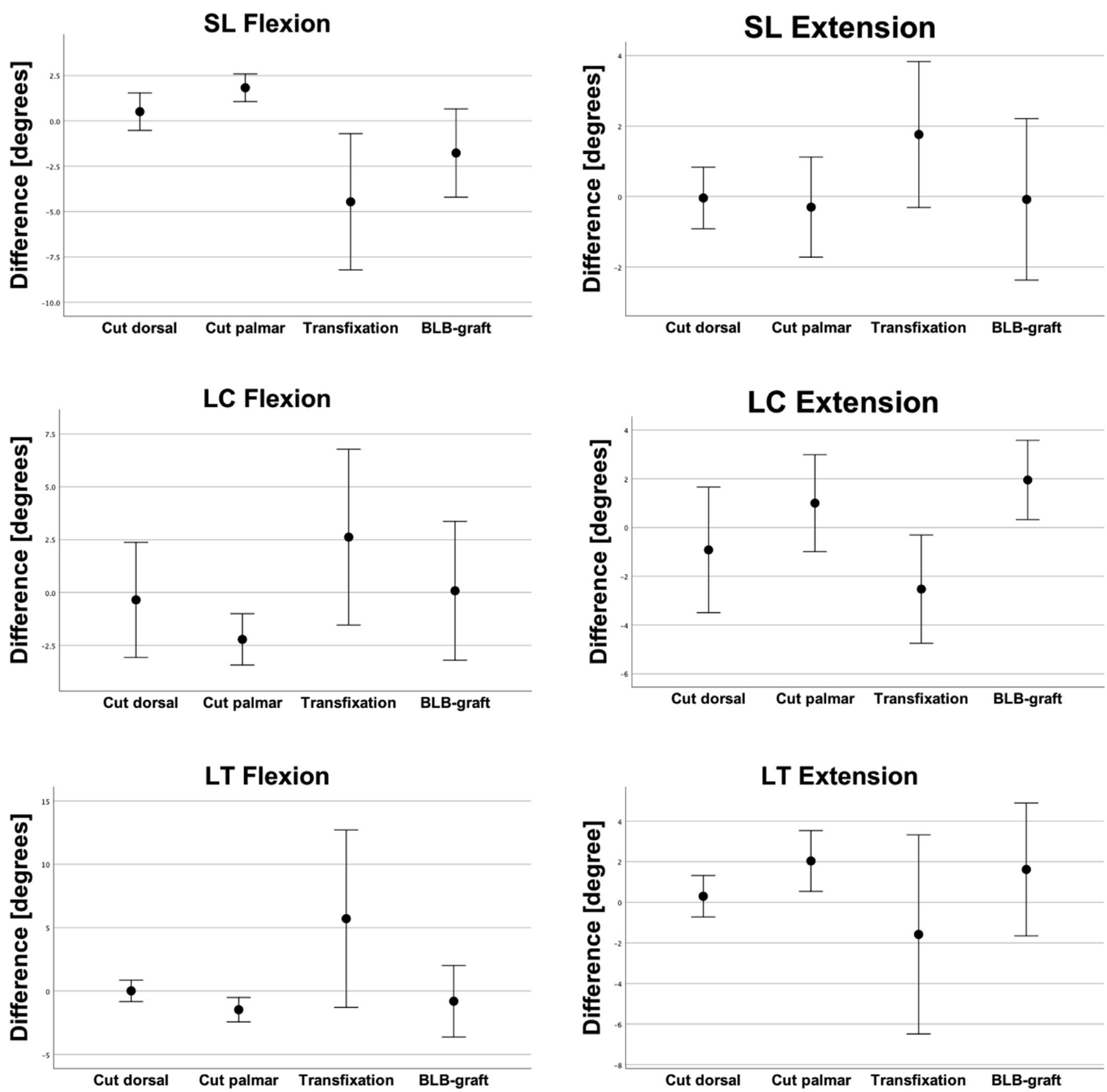

Figure 4. Differences in carpal motion changes relative to the intact state (degrees). BLB, bone–ligament–bone.

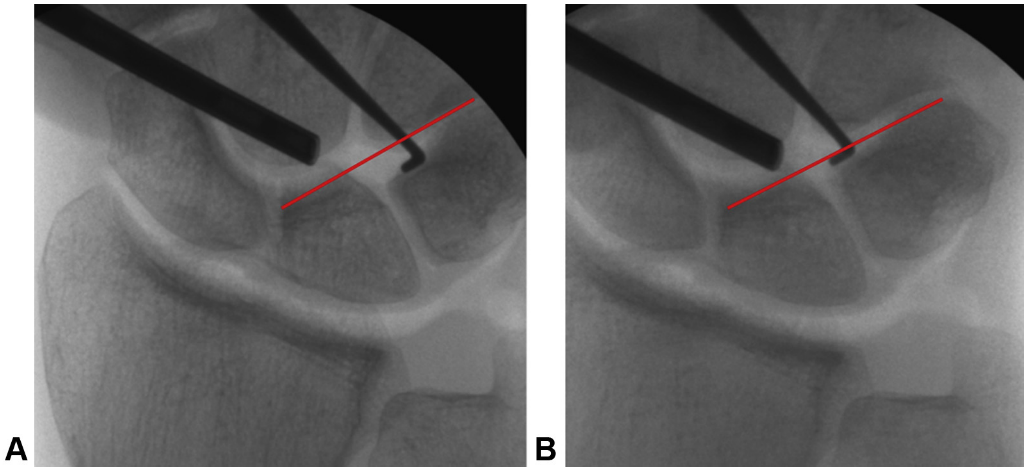

Figure 5. Clinical case: A 33-year-old man with an LT injury and instability on arthroscopic and radiologic examination. **A** Pressure application leading to widening of the LT joint. **B** Without pressure, return to normal alignment.

stability offers a simple option for treating LT instability with a single dorsal approach. Compared with an arthrodesis, the graft showed significantly less intercarpal motion in the adjacent SL and LC joints, thus partially restoring natural intercarpal motion. With regard to the LT joint, we found that intercarpal motion tended to be reduced after bone–ligament–bone reconstruction compared with a totally dissected LT ligament.

One example of a clinical case is a 33-year-old man who sustained a bicycle accident 1 year before surgery. A stressed x-ray showed malrotation of the LT joint as well as a lesion of the palmar part of the LT ligament. He had pain with rotation and weight-bearing. The diagnosis was confirmed arthroscopically and under an image intensifier (Fig. 5). A reconstruction was performed; 3 months later, the compression screw was removed after healing of the graft was confirmed (as is typically done). So as not to manipulate the joint further, the cortical screws were left *in situ*. The patient returned to work without pain when rotation the arm and bearing weight upon it. After 6 months, at the final follow-up, the Disabilities of the Arm, Shoulder, and Hand questionnaire score improved from 69.8 to 36.2 and the final Michigan Hand Outcomes Questionnaire score was 77.6. The final grip strength improved to 40.5 from 30 kg before surgery.

We acknowledge several limitations to this study. With 10 cadaveric forearms, there was only a small sample size to test different treatment options. To avoid opening and manipulating the LT joint from palmar, we decided to perform only sequential sectioning rather than dividing the specimens into 2 groups and comparing sectioning of the palmar part with sectioning of the dorsal part. Complete dissection of the LT ligament showed only a small amount of change in position; hence, the comparison of the reconstruction and arthrodesis with the dissected state is less significant. Additional cycles of motion might have increased the change after LT sectioning.[7] Also, some of the statistically significant differences were relatively small (1° to 4°); therefore, their clinical relevance is unclear.

With computed tomography imaging and 3-dimensional software calculating exact position changes in an entire body compared with only a few points, we used a clinically relevant method to evaluate carpal kinematics. However, owing to this new method, it is difficult to compare with those of previous studies. All results are given as relative data compared with the native state of each position, rather than demonstrating absolute data or compared with the neutral position. This may compensate for small irregularities in fixation in the jig, but it makes comparisons with other studies more difficult. Testing was done with cadaver forearms; therefore, we cannot evaluate the outcome of the reconstruction after tissue healing. However, to simulate consolidation, we also attached the bone–ligament–bone graft to the lunate and triquetrum with a cerclage. We did not perform a suture of the distally incised retinaculum because of a lack of literature on providing stability to the proximal carpal row and because a suture is not as stable as a healed retinaculum. Whether the distally incised retinaculum has an influence on the stability is unknown.

This study did not confirm biomechanical restoration of LT stability after reconstruction with a bone–ligament–bone graft. However, compared with arthrodesis, the bone–ligament–bone reconstruction displayed more physiologic carpal kinematics in the adjacent joints with enough stability but some mobility in the LT joint to treat chronic LT instability without the risk for nonunion. Indeed, compared with arthrodesis, less intercarpal motion could be observed in the adjacent joints. Therefore, in addition to promising clinical short-term results, we expect less strain on the adjacent joints with the bone–ligament–bone graft in the long term as a result of more physiological motion. Further clinical data with long-term follow-up are necessary to evaluate the advantage and validity of this treatment option in chronic LT instability.

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