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Does Proximal Hamate Graft for Proximal Scaphoid Reconstruction Restore Native Wrist Kinematics?

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Abstract

Background: The objective of this study was to determine whether reconstruction of the proximal pole of the scaphoid with a proximal hamate graft restores native carpal kinematics. **Methods:** A cadaveric study was designed assessing wrist kinematic after proximal hamate graft for proximal pole of the scaphoid nonunion. Wireless sensors were mounted to the carpus using a custom pin and suture anchor system to 8 cadavers. A wrist simulator was used to move the wrist through a cyclical motion about the flexion/extension and radial/ulnar deviation axes. Each specimen was tested under a series of 3 conditions: (1) a native state, "Intact"; (2) fractured scaphoid proximal pole, "Fracture"; and (3) post-reconstruction of the proximal pole of the scaphoid using a proximal hamate graft, "Graft." **Results:** The fracture condition resulted in a statistically significant change in scapholunate kinematics across the entire arc of motion relative to the intact condition. Reconstruction with proximal hamate grafts restored scapholunate kinematics close to the intact state in both flexion/extension and radial/ulnar deviation axes. The lunocapitate flexion during wrist flexion was significantly different after the hamate graft reconstruction. **Conclusions:** Proximal hamate to scaphoid transfer resulted in restoration of near normal carpal kinematics to the intact state.

Keywords: scaphoid nonunion, SNAC, unsalvageable proximal pole, hamate autograft

Introduction

Scaphoid fractures are the most common fractures occurring in the carpus and account for approximately 60% of all carpal fractures.[1] The incidence ranges from 1.5 to 39 per 100 000 person-years.[2-8]

The majority of the intraosseous vascularity to the scaphoid arises from branches of the radial artery entering the dorsal ridge.[9,10] The remainder of the blood supply enters volarly at the distal tuberosity of the scaphoid from branches of the radial artery.[10] This predominantly retrograde blood flow may account for why the proximal pole is predisposed to vascular insufficiency and is associated with the highest risk for developing nonunion and osteonecrosis.

The optimal strategy for the management of fragmented proximal scaphoid nonunions remains controversial.[1,10-16]

Several vascularized and nonvascularized autograft and allograft options for reconstruction of the proximal pole have been described with varying degrees of success.[18-20] Carter et al[21] reported on their experience of reconstructing the proximal pole with a scaphoid allograft. The authors reported satisfactory healing, pain relief, and range of motion in 6 of 8 cases. Sandow[22] described a technique for proximal pole reconstruction using a costo-osteochondral allograft. A review of 47 cases managed with this technique revealed that 85% of the patients rated their outcome as good or excellent and that the majority of patients were able to return to their preinjury vocation without activity modifications. In addition, by demonstrating maintenance of alignment of the scaphoid without dorsal intercalated segment nstability formation, Sandow reported that this technique seems to effectively reestablish the link between the proximal and distal carpal rows without necessitating reconstruction of the scapholunate (SL) ligament. Bürger et al[17] reported their experience using a vascularized medial femoral trochlea graft to reconstruct proximal pole nonunions. In their series of 16 cases, 15 healed and 12 of 16 patients had complete pain

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relief. In addition, average preoperative range of motion and the SL relationship were preserved.

While the feasibility and success of reconstruction of the proximal pole of the scaphoid with costo-osteochondral or vascularized medial femoral trochlea osteochondral grafts have been demonstrated, donor site morbidity can be a concern.[17,22,23] Elhassan et al[18] described a technique for reconstruction of the proximal pole of the scaphoid with the proximal hamate that also repairs the SL ligament. The proximal pole of the hamate is harvested with the volar capitohamate ligament, which is repaired to the remnant of the dorsal SL ligament once the graft is rotated and fixed. Kakar and colleagues, using manual and automated topographical analyses of the proximal hamate and scaphoid, noted that the majority of donor grafts would match the recipient site.[24] In an anthropometric assessment of the proximal pole of the hamate in a series of 29 cadavers, it was reported that 69% of hamates have the appropriate anatomy to serve as a graft for the proximal pole of the scaphoid,[25] emphasizing the importance for the surgeon to study the "matching suitability" of the graft to the proximal scaphoid.

The purpose of this study was to determine whether reconstruction of the proximal pole of the scaphoid with a proximal hamate graft restores native carpal kinematics.

Figure 1. Under fluoroscopic guidance, pins made from modified anchors were inserted into proximal part of the third metacarpal, distal pole of the scaphoid, distal part of the capitate, the lunate, and the distal radius.

Methods

A sample of convenience of 8 fresh-frozen, mid-forearm cadaver specimens was chosen for this institutionally approved study. Wireless sensors were mounted to the carpus using a custom pin and suture anchor system. Under fluoroscopic guidance, pins made from modified anchors were inserted into the proximal part of the third metacarpal, distal pole of the scaphoid, the capitate, the lunate, and the distal radius (Figure 1). The flexor carpi ulnaris (FCU), flexor carpi radialis (FCR), extensor carpi ulnaris (ECU), and extensor carpi radialis longus (ECRL) and brevis (ECRB) tendons were loaded during testing. This method of carpus tracking has been previously used and validated for similar carpal kinematic evaluations.[26-28]

A wrist simulator was used to move the wrist through a cyclical motion about the flexion/extension and radial/ulnar deviation axes.[28] The specimen was mounted to an unconstrained X-Y table using a vice-like clamp on the hand while the distal forearm was mounted via Kirschner (K) wires passing through the radius and ulna to a motor-driven stage that moved to create the desired wrist motion.[28] A stepper motor connected to the stage via timing belt pulleys created the desired arc of motion. A mild compressive force (15 N) was statically applied across the wrist using 4 pneumatic actuators sutured to the 5 tendons: FCU, FCR, ECU, and ECRL/ECRB to help stabilize the joint (Figure 2). The combination of the hand being mounted to an unconstrained X-Y stage and pneumatic muscle loading enabled the cadaveric limb to move about the desired axis of rotation in an unconstrained manner.

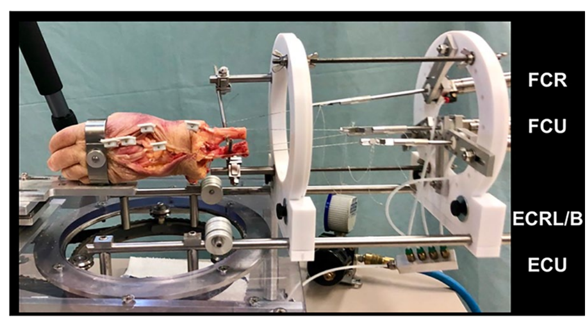

Figure 2. Experimental setup of the wrist stimulator: traction is consistently applied on the FCR, FCU, ECRB and ECRL, and ECU.
Note. FCR = flexor carpi radialis; FCU = flexor carpi ulnaris; ECRB = extensor carpi radialis brevis; ECRL = extensor carpi radialis longus; ECU = extensor carpi ulnaris.

Each specimen was tested under a series of 3 conditions: (1) a native state, "Intact"; (2) fractured scaphoid proximal pole, "Fracture"; and (3) post-reconstruction of the proximal pole of the scaphoid using a proximal 10-mm hamate graft, "Graft." Within each condition, the specimen was evaluated via cyclical testing about 2 functional axes of motion: flexion-extension and radial-ulnar deviation. The wrist underwent 100 cycles for each axis of motion driven by the mechanized movement of the forearm to ensure that the carpal positions and movement patterns had settled into patterns that were consistent.[28] The hand was cycled through each motion cycle at 70°/s. The position and orientation of the hand (tracked via a sensor on third metacarpal), scaphoid, lunate, capitate, and forearm (tracked via a sensor on radius) were recorded at 60 Hz using motion capture software (The MotionMonitor by Innovative Sports Training, Chicago, Illinois) for the final 5 cycles of motion. After each 100-cycle evaluation, the wrist was repositioned on the simulator to accommodate the next functional motion to be evaluated.

Kinematic motion was captured using a combination of Moiré Phase Tracking 3D motion tracking sensor hardware (MPT; Metria Innovation, Inc, Milwaukee, Wisconsin) and motion capture software (The MotionMonitor by Innovative Sports Training) to evaluate the hand, wrist, and forearm kinematics. Data were collected at 60 Hz using The Motion Monitor toolbox software (The MotionMonitor by Innovative Sports Training). This device enabled measurement of the 3-dimensional position and orientation of sensors attached to the bones relative to an absolute coordinate system generated by a single camera. The position and orientation accuracy of the system were 0.05° and 0.4 mm, respectively.[26-28] These sensors enabled accurate recording of the carpal motion without having a confounding effect on the carpal motion itself and were rigidly mounted to the radius, third metacarpal, capitate, lunate, and scaphoid. The anatomical coordinate systems of the hand and forearm were defined using a calibrated digitizing stylus according to the International Society of Biomechanics standards.[11] The coordinate systems of the capitate, lunate, and scaphoid were aligned to that of the hand (tracked via third metacarpal sensor) with the wrist in the neutral position. Euler angles were then computed with the rotation sequence about the anterior-posterior (flexion/extension), mediolateral (radial/ulnar deviation), and superior-inferior (pronation/supination) axes. The last 5 of the 100 cycles performed were averaged and used for kinematic analysis. SL, lunocapitate, and scaphoradial (SR) kinematics were evaluated during wrist flexion/extension and radial/ulnar deviation motions for each of the 3 conditions.

All carpal kinematics angles were computed at 5° intervals of both flexion/extension and radial/ulnar deviation axes. The intercarpal motion about both axes was analyzed for all wrist conditions. The differences between wrist conditions at each 5° interval were analyzed.

Surgical Technique

After performing measurements of the intact wrist, a proximal scaphoid pole osteotomy was performed to simulate a proximal scaphoid fracture. A longitudinal dorsal skin incision was made and the carpus approached through the extensor retinaculum between the third and fourth extensor compartments. A ligament sparing capsulotomy was then performed preserving the dorsal intercarpal (DIC) ligament. Under fluoroscopic guidance, we used an osteotome to create a fracture of the proximal pole of the scaphoid. The dorsal capsule and extensor retinaculum were then closed with 2-0 nonabsorbable suture prior to testing.

To reconstruct the proximal pole of the scaphoid, the proximal hamate was harvested using the proximal pole of the scaphoid as a template.[18] Care was taken to isolate the volar capitohamate ligament and detach it from its attachment to the capitate. The graft was inspected and modified to ensure that it matched the proximal scaphoid pole defect and adequately restored SL and scapho-capitate articulations. The graft was rotated 180°, reduced to the scaphoid, and temporarily secured with two 0.045 K-wires. Once satisfactory reduction was confirmed with direct visual inspection and with fluoroscopy, the graft was fixed with a cannulated 2.5-mm headless compression screw (Arthrex Laboratory, Naples, Florida; Figure 3). Fluoroscopy was used to confirm appropriate reduction and fixation of the proximal hamate graft using multiplanar views. The volar capitohamate ligament was then sutured to the remaining of the SL ligament that was attached to the lunate. The dorsal capsulotomy and the extensor retinaculum were repaired, and the specimen was mounted in preparation for testing.

Statistical Analysis

A multivariate repeated-measures analysis of variance (ANOVA) was performed with $P = .05$, comparing the SL and lunocapitate angles at each 5° interval of flexion/extension and radial/ulnar deviation between the 3 wrist conditions (intact, postscaphoid proximal pole fracture, and posthamate graft scaphoid reconstruction) with appropriate Greenhouse-Geisser corrections applied based on the results of Mauchly's sphericity tests. A Tukey HSD (honestly significant difference) post hoc test was performed in the event of statistical significance.

A power analysis was performed with power set at 80% to detect between-group differences in intercarpal kinematics equal to 1.6 standard deviations ($\alpha = 0.05$, 2-sided).

Results

Proximal row kinematics that occurred with wrist flexion-extension and radial-ulnar deviation are illustrated in Figures 4 to 6. For all conditions (intact, fractured, and reconstructed), the SL flexion/extension angle progression followed the same general pattern—from extension to flexion when the wrist was moved from an extended to flexed position (Figure 4a). There Were no statistically significant differences in SL flexion/extension angle during wrist

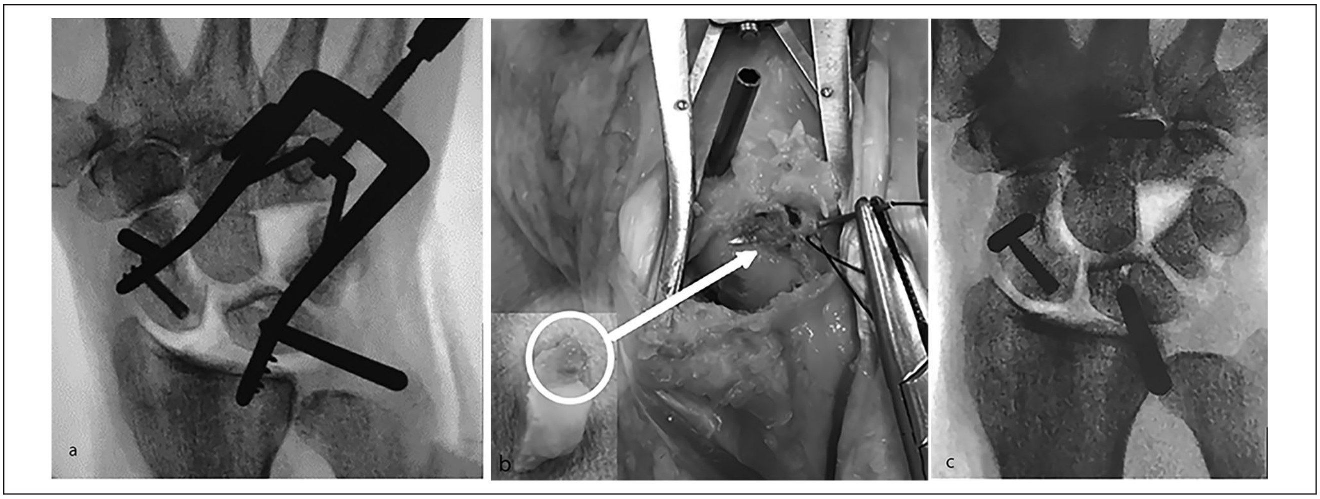

Figure 3. (a) Anteroposterior radiograph after proximal hamate pole fixation with a compression screw showing a persistent scapholunate gap. (b) Reconstruction of the dorsal scapholunate ligament with the volar capitohamate ligament. (c) Anteroposterior radiograph with screw fixation of the hamate and reconstruction of the scapholunate ligament showing reduction of the scapholunate gap.

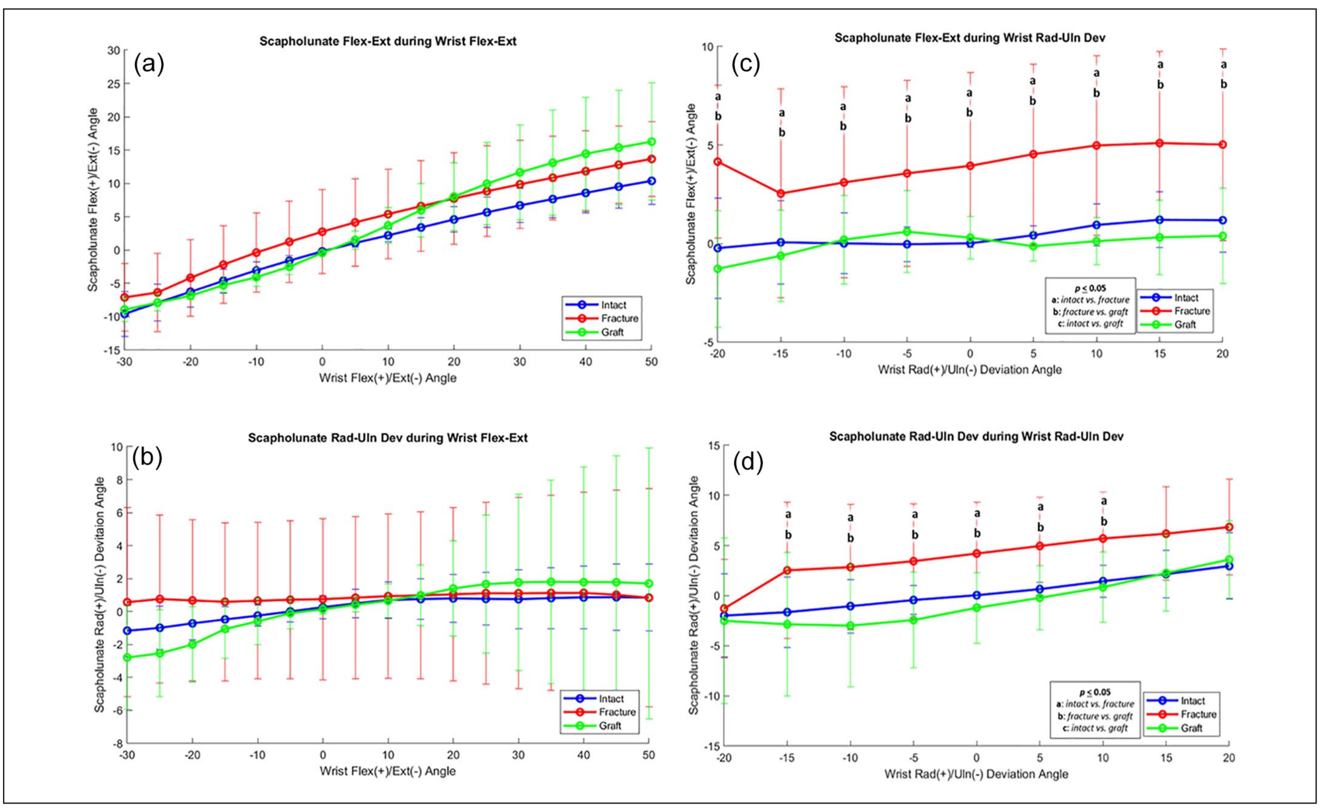

Figure 4. (a-d) Scapholunate motion angles during wrist range of motion in flexion-extension and radial-ulnar deviation.

flexion/extension between any conditions (P = .19-.60). Very little motion about the SL radial-ulnar deviation axis was present during wrist flexion/extension (Figure 4b). There were no statistically significant differences in SL flexion/extension angle during wrist flexion/extension between any conditions (P = .43-1.00).

The most notable change in SL kinematics occurred during wrist radial-ulnar deviation (Figures 4c and 4d). As the

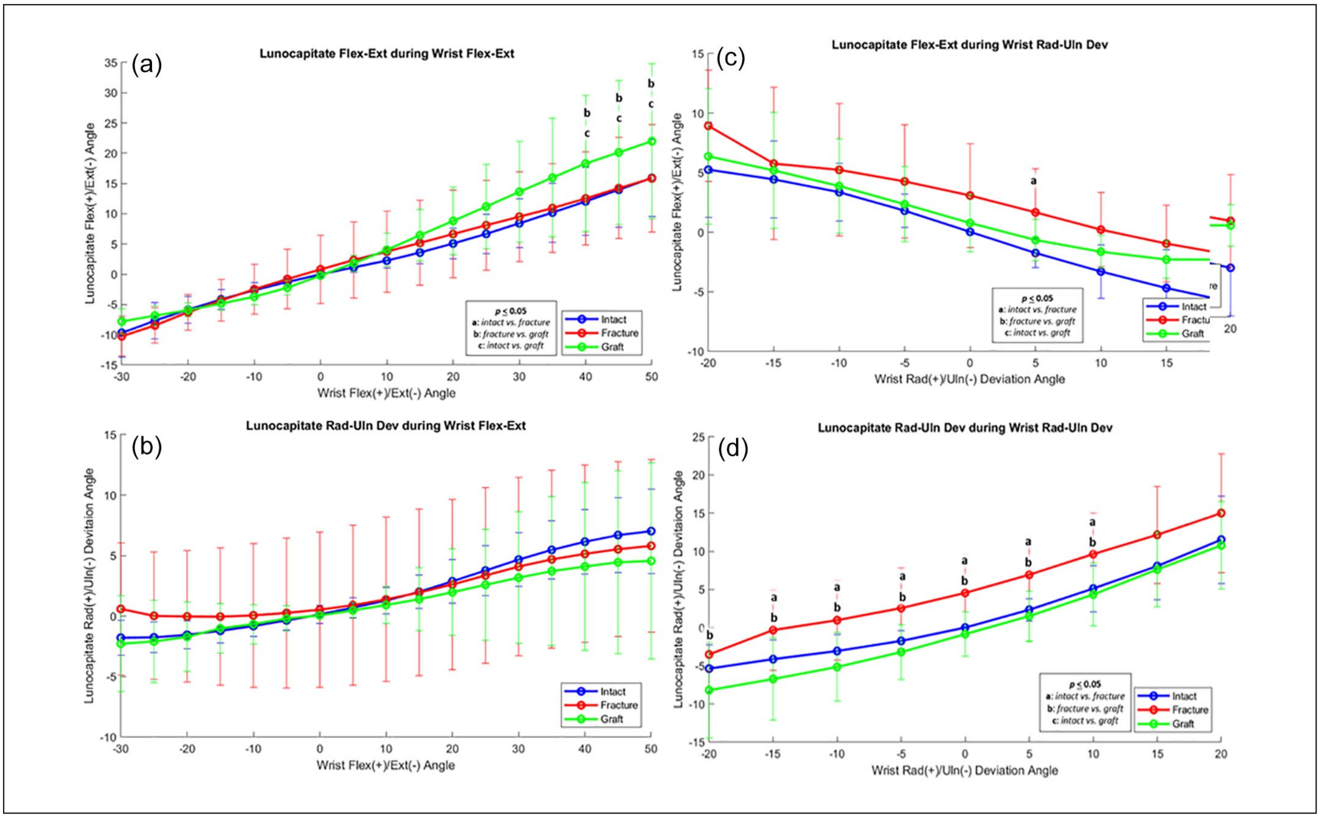

Figure 5. (a-d) Capitolunate motion angles during wrist range of motion in flexion-extension and radial-ulnar deviation.

wrist moved from ulnar to radial deviation during the intact condition, the SL flexion/extension angle was largely flat while the SL radial/ulnar deviation angle progressed from slight ulnar to slight radial deviation (Figure 4). However, in the scaphoid proximal pole fracture condition, the scaphoid assumed a more flexed and radially deviated position (Figures 4c and d). This change was statistically significant relative to the intact condition for SL flexion (over entire arc of wrist radial-ulnar deviation, P = .02-.05) and for SL radial-ulnar deviation (from 15° of wrist ulnar deviation to 10° of wrist radial deviation, P = .01-.03). Following the scaphoid proximal pole reconstruction, the graft resulted in a statistically significant change in SL kinematics relative to the fractured condition, including SL flexion (over entire arc of wrist radial-ulnar deviation, P = .004-.05) and SL radial-ulnar deviation (from 15° of wrist ulnar deviation to 10° of wrist radial deviation, P = .01-.03) (Figures 4c and d). No significant differences in SL kinematics were identified between the intact and reconstructed conditions during wrist radial-ulnar deviation for any wrist position (P = .53-.99). In all cases in which statistically significant differences in SL kinematics were created by the scaphoid proximal pole osteotomy, reconstruction of the proximal pole of the scaphoid with the proximal hamate restored SL motion closer to that of the intact state.

Midcarpal (lunocapitate) kinematics that occurred during wrist flexion-extension and radial-ulnar deviation are illustrated in Figure 5. There was no statistically significant change in lunocapitate flexion during wrist flexion after the creation of the fracture. However, there was a statistically significant increase in lunocapitate flexion during wrist flexion after the graft repair when the wrist was greater than 35° of flexion relative to both the intact (P = .02-.04) and fracture (P = .02-.04) conditions (Figure 5a). This indicates that when the wrist is in a flexed position greater than 35°, the reconstruction of the proximal pole of the scaphoid with the proximal hamate altered midcarpal motion while the creation of the fracture did not have an effect. During wrist radial-ulnar deviation (Figure 5c and d), the fractured condition resulted in a significant increase relative to the intact condition in lunocapitate flexion exclusively at 5° of radial deviation (P = .05) and in lunocapitate radial-ulnar deviation from 15° of wrist ulnar deviation to 10° of radial deviation (P = .04-.05). Following the scaphoid proximal pole reconstruction, the graft resulted in a statistically significant decrease in lunocapitate radial-ulnar deviation during wrist radial-ulnar deviation from 20° of wrist ulnar deviation to 10° of wrist radial-ulnar deviation (P = .01-.05). No statistically significant differences in lunocapitate kinematics during wrist radial-ulnar deviation were identi-

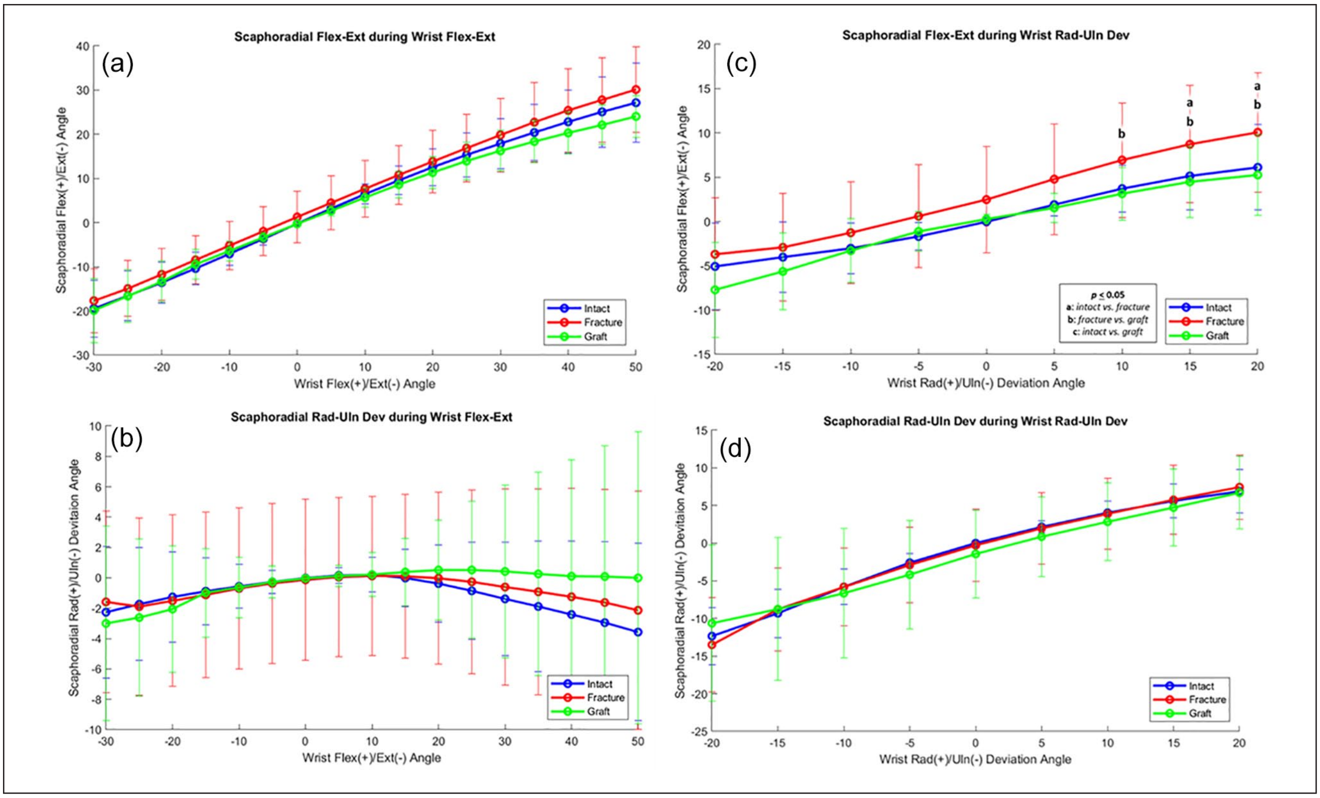

Figure 6. (a-d) Scaphoradial motion angles during wrist range of motion in flexion-extension and radial-ulnar deviation.

fied between the intact and reconstructed conditions. In all cases in which statistically significant differences were observed in the fracture state during wrist radial-ulnar deviation, reconstruction of the proximal pole of the scaphoid with the proximal hamate restored lunocapitate kinematics closer to their intact state.

Scaphoradial kinematics that occur with wrist flexion/extension and wrist radial-ulnar deviation are illustrated in Figure 6. For the intact, fracture, and reconstructed conditions, the SR angle progresses from extension to flexion and from ulnar to radial, and back to ulnar deviation (Figures 6a and b) when the wrist is moved from an extended to flexed position. When the wrist is moved from an ulnar deviated to radial deviated position, the SR angle progresses from extension to flexion and from ulnar to radial deviation for the intact, fracture, and reconstructed conditions (Figures 6c and d).

Scaphoradial kinematics were affected by the creation of the proximal pole fracture (Figure 6). During wrist radial-ulnar deviation, SR flexion increased relative to the intact condition when the wrist was greater than 10° of wrist radial deviation (P = .03-.05). Following the hamate graft repair of the proximal pole, the SR flexion statistically significantly decreased relative to the fracture condition when the wrist was greater than 5° of wrist radial deviation (P = .03-.05). No statistically significant differences in SR kinematics during wrist radial-ulnar deviation were identified between the intact and reconstructed conditions, indicating that the hamate graft procedure restored SR kinematics to their intact state.

Discussion

The purpose of this study was to determine what effect reconstruction of the proximal pole of the scaphoid with a proximal hamate graft had compared with native carpal kinematics. Our hypothesis was that reconstruction of the proximal pole of the scaphoid with a proximal hamate graft would restore native carpal kinematics. Our findings showed that reconstruction of the proximal pole of the scaphoid with the proximal hamate restored similar carpal kinematics compared with the intact state.

One of the advantages of the proximal hamate graft is that it is harvested with the volar capitohamate ligament, which facilitates SL ligament repair.[18] Ritt et al[23] demonstrated that the volar capitohamate ligament is stronger than the dorsal component of the ligament. Repair of the SL ligament may mitigate the risk of carpal instability, although further clinical studies are needed to validate this.

We reported an increased flexion of the lunocapitate joint when the wrist was in a flexed position greater than 35°; the reconstruction of the proximal pole of the scaphoid with the proximal hamate altered lunocapitate flexion while the creation of the fracture did not have an effect. This highlights the importance of matching the hamate graft to the size of the proximal pole of the scaphoid. While we feel the hamate is a viable graft replacement, as noted by Kakar and colleagues[24] and Wu et al,[25] not all proximal hamates are suitable for this procedure. We therefore carefully analyze the preoperative computed tomography (CT) scan to determine graft suitability on all cases.

One concern regarding harvesting the proximal hamate graft is the possible altered carpal kinematics that may occur. This has not been borne out by other studies looking at the management of hamate arthrosis lunotriquetral ligament tear (HALT) lesions.[29] Harley et al[29] resected the proximal hamate in 6 cadaveric wrists and demonstrated that loading across the triquetrohamate joint was not altered. More recently, Kakar et al[28] specifically evaluated the effect of proximal hamate resection on radiocarpal and midcarpal kinematics. The authors demonstrated that there were no differences in lunocapitate and SL motion during wrist flexion-extension and radial-ulnar deviation between the intact and proximal hamate resection conditions. This study has several limitations. First, we attempted to simulate in vivo wrist motion by mounting the specimen to an unconstrained X-Y platform and loading wrist flexors and extensors so that the carpus could move about the desired axis of rotation in an unconstrained manner. This setup allowed motion of the wrist in various directions by applying traction to the principal wrist flexor and extensor tendons. By using dedicated wrist sensors inserted into carpal bones, this allowed for precise and accurate measurements of carpal kinematics in the different states. While this tends to mimic wrist motion, it may not, however, reproduce the physiological motion of the wrist. In addition, the wrist was cycled 100 times and loaded with a compressive force of 15 N. This may underestimate the true physiologic load and motions a wrist is subjected to on a daily basis and thus is a limitation of cadaveric testing. A clinical study with long-term follow-up would be necessary to confirm those statements. We chose a sample size of convenience of 8 cadavers and so there is a risk of a Type 1 error. Nonetheless, the trends of the findings were consistent which we felt reflected the changes seen within the intact, fractured, and reconstructed states. Cadaveric tissue has inherent differences in pliability compared with living tissue and may have deteriorated during testing conditions. In addition, the sequential progression used in the cadaveric model may have affected the results through the testing states in each specimen. We kept the testing sequence constant between all specimens to try and mitigate this limitation. While this study primarily assessed carpal kinematics, it did not study the ability of the grafts to unite. This is of utmost clinical importance, and long-term outcome studies of this nonvascularized graft are needed.

Notwithstanding these limitations, this study aims to highlight that reconstruction of the proximal pole of the scaphoid with a proximal hamate graft may approximate carpal kinematics after a proximal scaphoid fracture. The proximal hamate graft is harvested from the same operative field, permits reconstruction of the SL ligament, and may be considered as a potential treatment option for unsalvageable proximal pole scaphoid nonunions. Long-term clinical studies are needed to assess the efficacy of this procedure.

Authors' Note

Marion Burnier is now affiliated to ICMMS, Clinique du Medipole, Villeurbanne, France. Bassem Elhassan is now affiliated to Massachusetts General Hospital. Joe Gil is now affiliated to Brown University.

Author Contributions

All authors were actively involved in the planning, enactment, and writing up of this study.

Ethical Approval

This study was approved by our institutional review board.

Statement of Human and Animal Rights

All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2008 (5).

Statement of Informed Consent

Informed consent was obtained from all patients for being included in the study.

Declaration of Conflicting Interests

The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: B.E. has Royalties or license with DJO: Design team and consulting fees with DJO Arthrex; S.K. has financial/nonfinancial interests with *ASSH Hand E*, *BJJ*, and *JBJS*, and consulting fees from Arthrex; the rest of the authors declare that they have no conflict of interest.

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References

1. Aibinder WR, Wagner ER, Bishop AT, et al. Bone grafting for scaphoid nonunions: is free vascularized bone grafting superior for scaphoid nonunion? *Hand*. 2019;14:217-222.
2. Beingessner DM, Dunning CE, Gordon KD, et al. The effect of radial head excision and arthroplasty on elbow kinematics and stability. *J Bone Joint Surg Am*. 2004;86:1730-1739.
3. Duckworth AD, Jenkins PJ, Aitken SA, et al. Scaphoid fracture epidemiology. *J Trauma Acute Care Surg*. 2012;72: E41-E45.
4. Dy CJ, Kazmers NH, Baty J, et al. An epidemiologic perspective on scaphoid fracture treatment and frequency of nonunion surgery in the USA. *HSS J*. 2018;14:245-250.
5. Larsen CF, Brondum V, Skov O. Epidemiology of scaphoid fractures in Odense, Denmark. *Acta Orthop Scand*. 1992; 63:216-218.
6. Raittio LT, Jokihaara J, Huttunen TT, et al. Rising incidence of scaphoid fracture surgery in Finland. *J Hand Surg Eur Vol*. 2018;43:402-406.
7. Van Tassel DC, Owens BD, Wolf JM. Incidence estimates and demographics of scaphoid fracture in the U.S. population. *J Hand Surg Am*. 2010;35:1242-1245.
8. Zura R, Xiong Z, Einhorn T, et al. Epidemiology of fracture nonunion in 18 human bones. *JAMA Surg*. 2016;151: e162775.
9. Gelberman RH, Menon J. The vascularity of the scaphoid bone. *J Hand Surg Am*. 1980;5(5):508-513.
10. Kang KB, Kim HJ, Park JH, et al. Comparison of dorsal and volar percutaneous approaches in acute scaphoid fractures: a meta-analysis. *PLoS ONE*. 2016;11(9):e0162779.
11. Ecker J. Scaphoid union: the role of wrist arthroscopy. *Hand Clin*. 2017;33:677-686.
12. Ernst SMC, Green DP, Saucedo JM. Screw fixation alone for scaphoid fracture nonunion. *J Hand Surg Am*. 2018;43: 837-843.
13. Jauregui JJ, Seger EW, Hesham K, et al. Operative management for pediatric and adolescent scaphoid nonunions: a meta-analysis. *J Pediatr Orthop*. 2019;39:e130-e133.
14. Lee YK, Choi KW, Woo SH, et al. The clinical result of arthroscopic bone grafting and percutaneous K-wires fixation for management of scaphoid nonunions. *Medicine*. 2018; 97(13):e9987.
15. Putnam JG, DiGiovanni RM, Mitchell SM, et al. Plate fixation with cancellous graft for scaphoid nonunion with avascular necrosis. *J Hand Surg Am*. 2019;44(4):339.e1-339.e7.
16. Regal S, Chauhan A, Tang P. The radial aspect of the distal radial metaphysis/diaphysis as a source of cortical bone graft. *J Hand Surg Am*. 2017;42(7):577.e1-577.e5.
17. Burger HK, Windhofer C, Gaggl AJ, et al. Vascularized medial femoral trochlea osteocartilaginous flap reconstruction of proximal pole scaphoid nonunions. *J Hand Surg Am*. 2013;38:690-700.
18. Elhassan B, Noureldin M, Kakar S. Proximal scaphoid pole reconstruction utilizing ipsilateral proximal hamate autograft. *Hand*. 2016;11:495-499.
19. Garcia-Elias M, Lluch A. Partial excision of scaphoid: is it ever indicated? *Hand Clin*. 2001;17:687-695.
20. Yao J, Read B, Hentz VR. The fragmented proximal pole scaphoid nonunion treated with rib autograft: case series and review of the literature. *J Hand Surg Am*. 2013;38:2188-2192.
21. Carter PR, Malinin TI, Abbey PA, et al. The scaphoid allograft: a new operation for treatment of the very proximal scaphoid nonunion or for the necrotic, fragmented scaphoid proximal pole. *J Hand Surg Am*. 1989;14:1-12.
22. Sandow MJ. Proximal scaphoid costo-osteochondral replacement arthroplasty. *J Hand Surg Br*. 1998;23:201-208.
23. Ritt MJ, Berger RA, Kauer JM. The gross and histologic anatomy of the ligaments of the capitohamate joint. *J Hand Surg Am*. 1996;21:1022-1028.
24. Kakar S, Greene RM, Elhassan BT, et al. Topographical analysis of the hamate for proximal pole scaphoid nonunion reconstruction. *J Hand Surg Am*. 2020;45(1):69.e1-69.e7.
25. Wu K, Padmore C, Lalone E, et al. An anthropometric assessment of the proximal hamate autograft for scaphoid proximal pole reconstruction. *J. Hand Surg. Am*. 2019;44:60.e1-60.e8.
26. Hooke AW, Thoreson AR, Hewett T, et al. A novel method for evaluation of carpal kinematics in a cadaveric model. International Society of Biomechanics, Calgary, AB, Canada, July 31-August 4, 2019.
27. Alolabi N, Hooke AW, Kakar S. The biomechanical consequences of trapeziectomy and partial trapezoidectomy in the treatment of thumb carpometacarpal and scaphotrapeziotrapezoid arthritis. *J Hand Surg Am*. 2020;45(3):257.e1-257.e7.
28. Kakar S, Greene RM, Hewett T, et al. The effect of proximal hamate osteotomy on carpal kinematics for reconstruction of proximal pole scaphoid nonunion with avascular necrosis. *Hand*. 2020;15(3):371-377.
29. Harley BJ, Werner FW, Boles SD, et al. Arthroscopic resection of arthrosis of the proximal hamate: a clinical and biomechanical study. *J Hand Surg Am*. 2004;29:661-667.