ARTICLE IN PRESS

SCIENTIFIC ARTICLE

Elongation of the Dorsal Carpal Ligaments: A Computational Study of *In Vivo* Carpal Kinematics

Michael J. Rainbow, PhD, Joseph J. Crisco, PhD, Douglas C. Moore, MS, Robin N. Kamal, MD, David H. Laidlaw, PhD, Edward Akelman, MD, Scott W. Wolfe, MD

Purpose The dorsal radiocarpal (DRC) and dorsal intercarpal (DIC) ligaments play an important role in scapholunate and lunotriquetral stability. The purpose of this study was to compute changes in ligament elongation as a function of wrist position for the DRC and the scaphoid and trapezoidal insertions of the DIC.

Methods We developed a computational model that incorporated a digital dataset of ligament origin and insertions, bone surface models, and *in vivo* 3-dimensional kinematics (n = 28 wrists), as well as an algorithm for computing ligament fiber path.

Results The differences between the maximum length and minimum length of the DRC, DIC scaphoid component, and DIC trapezoidal component over the entire range of motion were 5.1 ± 1.5 mm, 2.7 ± 1.5 mm, and 5.9 ± 2.5 mm, respectively. The DRC elongated as the wrist moved from ulnar extension to radial flexion, and the DIC elongated as the wrist moved from radial deviation to ulnar deviation.

Conclusions The DRC and DIC lengthened in opposing directions during wrist ulnar and radial deviation. Despite complex carpal bone anatomy and kinematics, computed fiber elongations were found to vary linearly with wrist position. Errors between computed values and model predictions were less than 2.0 mm across all subjects and positions.

Clinical relevance The relationships between ligament elongation and wrist position should further our understanding of ligament function, provide insight into the potential effects of dorsal wrist incisions on specific wrist ranges of motion, and serve as a basis for modeling of the wrist. *(J Hand Surg 2012;xx:. Copyright © 2012 by the American Society for Surgery of the Hand. All rights reserved.)*

Key words Carpal, dorsal, *in vivo*, kinematics, ligaments.

THE WRIST IS unique in that the motions of its component carpal bones are determined almost exclusively by cartilage contact and ligament forces, rather than by direct muscular attachments. Many surgical interventions attempt to restore ligament function,[1–2] yet little is known about the *in vivo* mechanical behavior of the ligaments. One set of ligaments that has not been extensively studied *in vivo* is the set of extrinsic dorsal carpal ligaments. The dorsal carpal ligaments consist of the dorsal intercarpal ligament (DIC)

From the Department of Orthopaedics, The Warren Alpert Medical School of Brown University and Rhode Island Hospital, Providence, RI; Department of Computer Science, Brown University, Providence, RI; Hospital for Special Surgery and Weill Medical College of Cornell University, New York, NY.

Received for publication July 28, 2011; accepted in revised form April 18, 2012.

The authors would like to acknowledge the Division of Biomechanics and Bone Physiology Research at the University of Texas Medical Branch, Department of Orthopaedic Surgery and Rehabilitation, for their contribution of 3-dimensional bone structures with ligament attachment regions.

No benefits in any form have been received or will be received related directly or indirectly to the subject of this article.

Funded by the National Institutes of Health (NIH) HD052127 and AR053648.

Corresponding author: Joseph J. Crisco, PhD, Department of Orthopaedics, Bioengineering Laboratory, Warren Alpert Medical School of Brown University/Rhode Island Hospital, 1 Hoppin Street, CORO West, Suite 404, Providence, RI 02903; e-mail: joseph_crisco@brown.edu.

0363-5023/12/xx0x-0001$36.00/0
http://dx.doi.org/10.1016/j.jhsa.2012.04.025

and the dorsal radiocarpal (DRC) ligament,[3] which together form a lateral V shape, originating on the triquetrum and inserting on the scaphoid, and originating on the radius and inserting on the triquetrum, respectively. Although these ligaments have been characterized as less substantive than their volar counterparts,[4] recent studies have suggested that they play an important role in scapholunate stability and lunotriquetral stability.[5–7]

Determining how a ligament elongates as a function of wrist position is a crucial step in understanding ligament function. Much of the previous work on carpal ligaments has focused on mechanical testing and anatomical descriptions of the ligaments and their origin and insertion sites.[3–4,6,8–9] Measuring ligament length changes as a function of wrist position in living subjects is a challenge because current imaging modalities are limited in their ability to simultaneously resolve bone surfaces, kinematics, and soft tissue morphology. The current state of the art for *in vivo* imaging of the carpal ligaments is limited to identification of major ligaments and pathological conditions.[10,11]

Computational models can be powerful tools for evaluating wrist kinematics and ligament function. These models have previously provided insights into pathology of the distal radioulnar joint.[12] In addition, they have determined which wrist motions are likely to cause the carpal ligaments to become taut.[13–14] The elongation of the DRC and DIC ligaments have been previously studied along specific paths of ulnar-radial deviation (UR)[15] and a dart thrower's path[16] using this approach. The purpose of this study was to determine the relationship between fiber elongation and wrist position of these 2 important dorsal carpal ligaments through the full range of wrist motion.

METHODS

Carpal bone surfaces and kinematics

After institutional review board approval and informed consent, computed tomography images of both wrists of 8 healthy men (mean age, 24 y; range, 22–26 y) and 6 healthy women (mean age, 25 y; range, 21–28 y) were taken in 9 wrist positions as part of another study.[17] The right and left wrists were scanned simultaneously using a GE HiSpeed Advantage computed tomography scanner (GE Healthcare Technologies, Waukesha, Wisconsin) with settings of 120 kVP and 80 mAs, in plane resolution of 0.9 × 0.9 mm^2, and slice thickness of 1.0 mm. Digital bone surface models for each subject were obtained through segmentation of the computed tomography volumes (Analyze, Mayo Clinic Foundation, Rochester, MN) and tessellation using Geomagic Studio (Raindrop Geomagic, Research Triangle Park, NC). Kinematic transformations from the neutral wrist position to the remaining positions were calculated using a previously reported, markerless bone registration technique.[18–19] Briefly, the technique first identified tissue-classified voxels associated with the segmented point cloud of each carpal bone in the neutral position, and then the algorithm optimized the fit between the neutral position voxels and voxels in each subsequent scan, computing the change in bone posture with sub-voxel accuracy.[19] Actual wrist position was defined by the position of the capitate with respect to the radius.[20] The targeted wrist positions of neutral, 40° flexion (F), 40° extension (E), 10° radial deviation (R), 30° ulnar deviation (U), and the combined motions of 40° E and 30° U, 40° F and 30° U, 40° E and 10° R, and 40° F and 10° R resulted in a range of wrist motion for all subjects of 34° F to 62° E and 35° U to 27° R. The actual range of wrist motion per subject was 29° ± 6° ulnar radial deviationUR and 69° ± 8° flexion–extension (FE).[17]

Selection of ligament insertion regions

The DRC and DIC ligaments insert on multiple bones and interdigitate with other ligaments. Only the largest portions of the DRC and DIC ligaments with insertion areas greater than 4 mm^2 were modeled in the present study.[21] These included the main band of the DRC ligament, which originates on the dorsal medial ridge of the radius, passes over the lunate, and inserts onto the dorsal pole of the triquetrum. They also included the main bundles of the DIC ligament, which originate on the dorsal pole of the triquetrum and pass over the hamate, lunate, and capitate to insert onto the dorsal ridge of the scaphoid (DIC_S) and the dorsal aspect of the trapezoid (DIC_T).[3] These attachments of the DRC, DIC_S, and DIC_T ligaments have been reported to be present in 100%, 97%, and 42% of people, respectively.[6] The regions of insertion were mapped to each subject's bone surface model using a template created in a previous study through careful digitization of insertion sites on cadaver bones, which were then registered to the corresponding bone surface model.[22] Insertion site mapping was performed manually using Geomagic Studio, with both models opened simultaneously for visual comparison (Fig. 1).

Ligament fiber generation

Fibers for all 3 ligaments (DRC, DIC_S, and DIC_T) were modeled as paths of points that traversed the shortest possible distance between insertion sites, with the constraint that the bone surface models were not penetrated

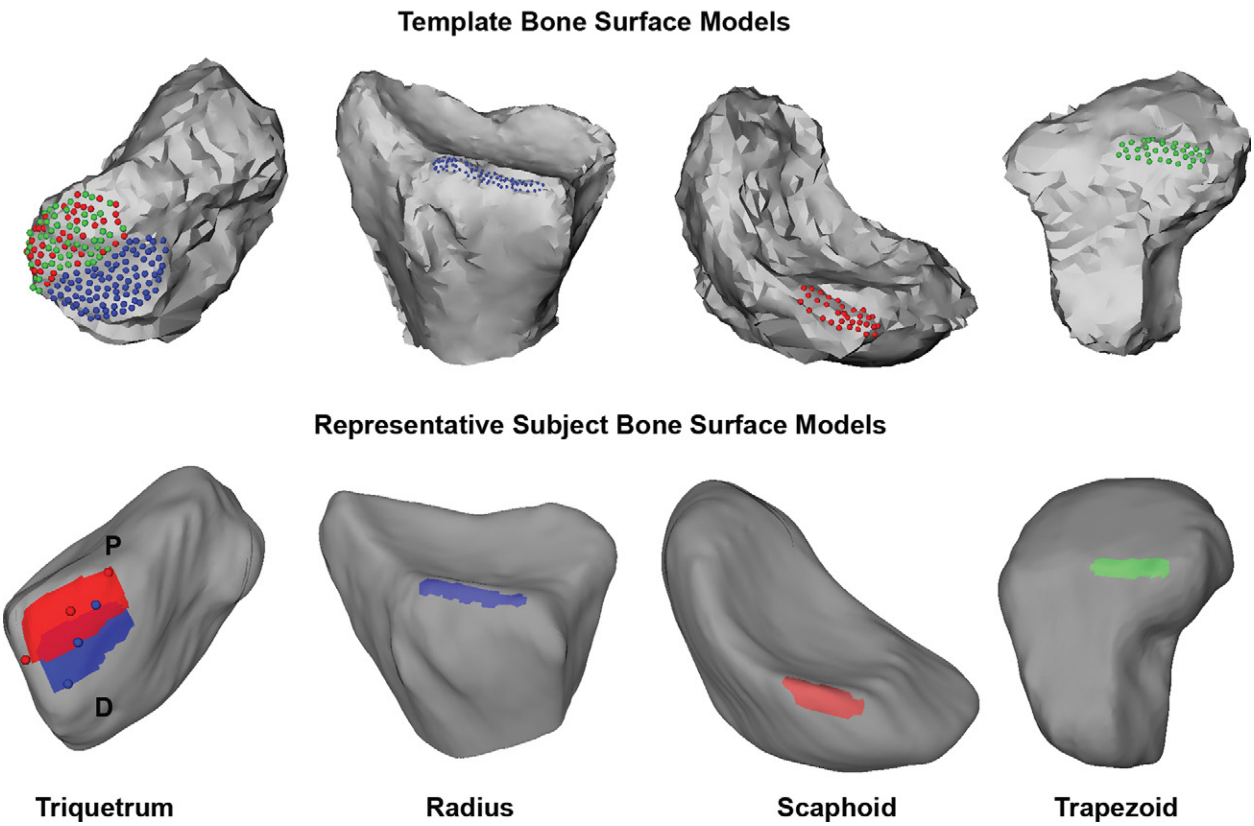

FIGURE 1: The template[22] insertion bone surface model (top) with points representing the insertion regions for the DRC (blue), DIC_S (red), and DIC_T (green), and a representative subject's bone surface model (bottom) with polygons selected to match the template insertion regions. The points on the subject's triquetrum represent the 3 fibers analyzed: the most proximal point located on the perimeter, the most distal point, and a point in the center of the insertion region.

(Fig. 2).[23] Each fiber contained 40 discrete points (39 segments), and the length of each ligament fiber at each wrist position was defined as the distance along its path. A central fiber was defined between the central points of corresponding attachment regions. Two additional fibers were also defined, using the most proximal and distal aspects of the triquetrum insertion region. The fibers were roughly parallel to the central fiber based on previous qualitative studies that showed that individual fibers were primarily aligned with the course of the ligament.[8,24] The paths and lengths of the central, proximal, and distal fibers were computed for each subject in each of the 9 widely distributed wrist positions. The total excursion of each ligament fiber was defined as the difference between its minimum and maximum length across all 9 wrist positions.

Analysis

We evaluated the relationship between fiber length and wrist position using hierarchical linear modeling (HLM). Hierarchical linear modeling can be conceptualized as a set of subject-specific, best-fit planes fit to the wrist position and fiber length data, with wrist position as the independent variable and fiber length as the dependent variable. The length of each fiber at the neutral position (0° FE and 0° UR) was used to define the intercept of the model. The coefficients of the best-fit model, termed *elongation rates*, reflect the change in fiber length per change in wrist position. The HLM evaluated the model parameters using a hierarchy of 3 levels. The first level contained the central, proximal, and distal fibers within each ligament; the second contained each ligament within a subject's wrist; and the third contained all wrists within the study population. The HLM used residual estimation of maximum likelihood to simultaneously evaluate ligament lengths at each level of the hierarchy, as well as the interactions between levels and within each level.[25]

The fidelity of the HLM was reported in terms of the root-mean-squared error between the ligament lengths computed from the *in vivo* data set and the lengths estimated by the HLM. The HLM was used to determine the elongation rate along 4 specific paths of wrist motion: pure FE (with UR set to 0°), pure UR (with FE

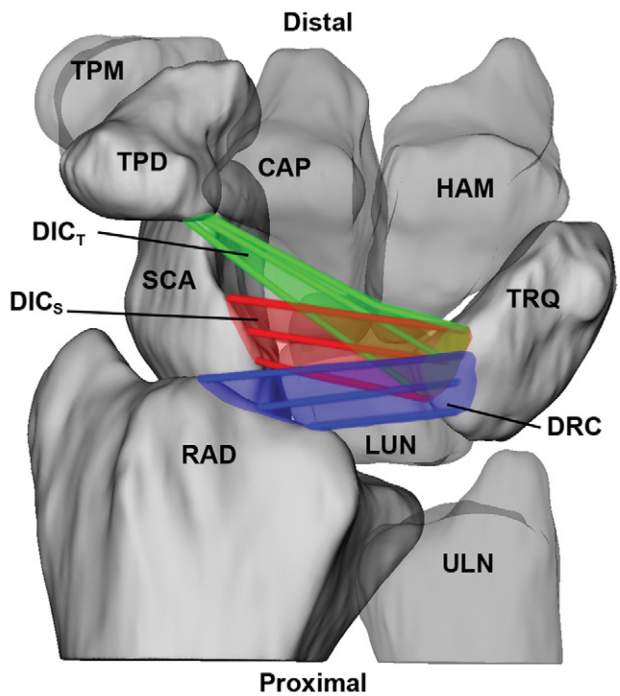

FIGURE 2: Right wrist, dorsal view. The proximal, central, and distal fibers of the DRC (blue), DIC_S (red), and DIC_T (green) of a subject in a slightly extended wrist position. TPM, trapezium; TPD, trapezoid; CAP, capitate; HAM, hamate; SCA, scaphoid; TRQ, triquetrum; LUN, lunate; RAD, radius; ULN, ulna.

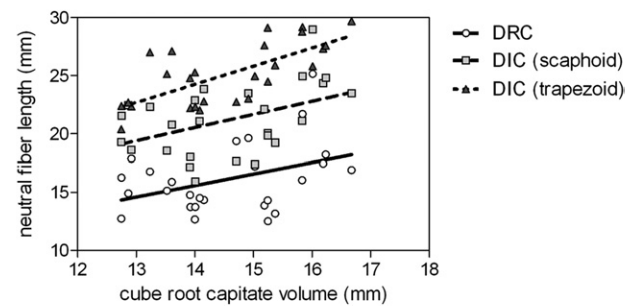

FIGURE 3: Neutral fiber length versus the cube root of the capitate's volume. The neutral fiber length increased significantly with increasing wrist size as measured by capitate volume ($P <$ .05). This size effect is accounted for by the hierarchical linear model, as it models length changes from neutral of each subject.

set to 0°), the dart thrower's path (radial extension to ulnar flexion), and the anti-dart thrower's path (ulnar extension to radial flexion). The dart thrower's and anti-dart thrower's paths were oriented 45° to the FE and UR paths and passed through 0° FE and 0° UR. The HLM model tested which paths of wrist motion significantly lengthened each ligament. The HLM determined whether the fibers within a ligament had significantly different elongation rates. The threshold for statistical significance was set *a priori* at $P < .05$. The HLM also predicted which paths of wrist motion minimized the elongation rate. In other words, it identified the paths of wrist motion in which the fiber length was constant. These minimal paths were reported for each ligament in terms of degrees of FE per degree of UR.

RESULTS

There were no statistically significant differences in elongation rates between the central, distal, and proximal fibers within each ligament as the wrist moved through its range of motion. Therefore, the results are reported at the ligament level. The mean total excursions were 5.1 ± 1.5 mm for the DRC ligament, 2.7 ± 1.5 mm for the DIC_S ligament, and 5.9 ± 2.5 mm for the DIC_T ligament. The average neutral lengths estimated by the HLM were 16.1 ± 3.7 mm, 21.8 ± 4.2 mm, and 26.0 ± 4.2mm, for the DRC, DIC_S, and DIC_T ligaments, respectively. Neutral fiber length of each ligament was found to increase significantly ($P < .05$) with an increase in size of the subject's capitate (Fig. 3).

Fiber length varied linearly with wrist position for the DRC, DIC_S, and DIC_T ligaments, as reflected in low root-mean-squared errors between the computed and HLM-estimated fiber lengths, which were 1.0 mm, 1.8 mm, and 1.2 mm for the DRC, DIC_S, and DIC_T ligaments, respectively.

Ulnar-radial deviation

The DRC ligament significantly lengthened during radial deviation ($P < .001$), whereas the DIC_S and DIC_T ligaments significantly lengthened with wrist ulnar deviation ($P < .001$) (Fig. 4A–B). The elongation rate of the DRC ligament was 0.078 ± 0.009 mm/degree (standard error of the mean) of wrist radial deviation, whereas the elongation rates of the DIC_S and DIC_T ligaments were 0.053 ± 0.009 mm/degree and 0.147 ± 0.009 mm/degree of wrist ulnar deviation, respectively.

Flexion extension

The DRC ligament lengthened significantly ($P < .001$) with flexion, with an elongation rate of 0.051 ± 0.003 mm/degree of wrist flexion (Table 1). Neither wrist flexion nor extension lengthened the DIC_S ligament ($P = .37$). The DIC_T ligament lengthened ($P < .001$) with an elongation rate of 0.023 ± 0.03 mm/degree of wrist flexion (Fig. 4 C–D).

Dart thrower's path (wrist radial extension to ulnar flexion)

The DRC ligament lengthened with an elongation rate of 0.040 ± 0.008 mm/degree of wrist motion along a

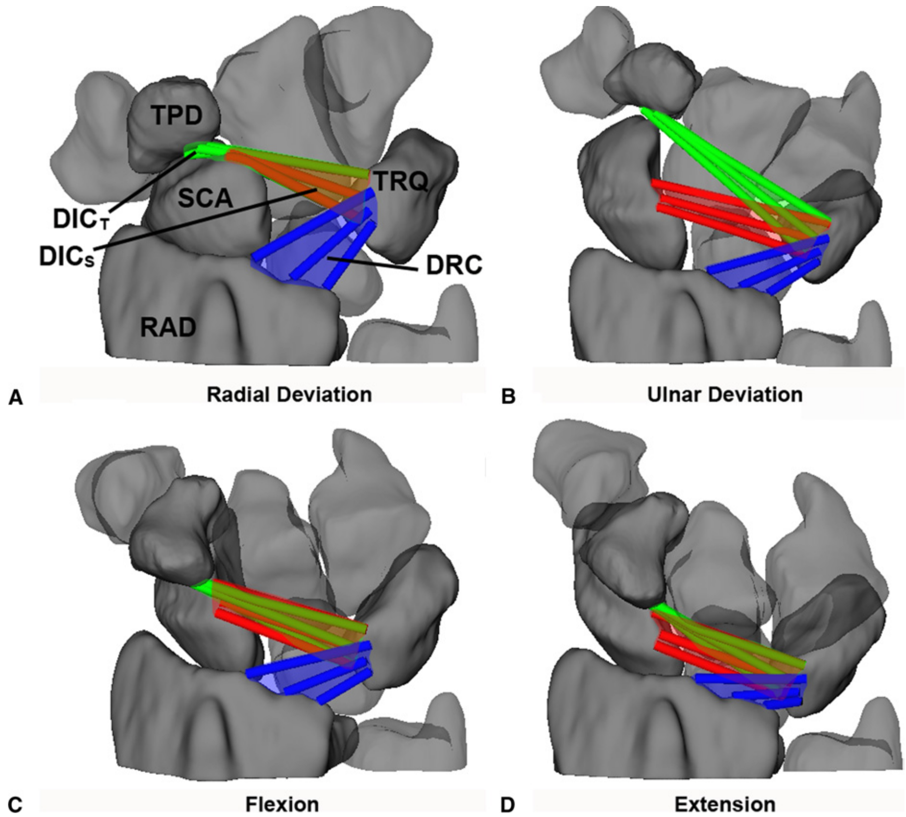

FIGURE 4: Ligament fiber path computed for a representative wrist in **A** radial deviation, **B** ulnar deviation, **C** flexion, and **D** extension. TPD, trapezoid; SCA, scaphoid; TRQ, triquetrum; RAD, radius.

TABLE 1. Ligament Elongation Rates Predicted by Hierarchical Linear Modeling

Ligament	Neutral Length (mm) (Standard Error)	U(+) R(−)	F(+) E(−)	UF(+) RE(−) Dart Thrower's Path	RF(−) UE(+) Anti-Dart Thrower's Path
DRC	16.1 (0.7)	(−) 0.078 (0.009)*	0.051 (0.003)*	(−) 0.04 (0.008)*	(−) 0.084 (0.004)*
DIC_S	22.2 (0.8)	0.053 (0.009)*	0.001 (0.003)	0.045 (0.008)*	0.027 (0.004)*
DIC_T	25.6 (0.8)	0.147 (0.009)*	0.023 (0.003)*	0.137 (0.008)*	0.058 (0.004)*

Ligament elongation rates predicted by HLM in the direction of flexion–extension (FE), ulnar radial deviation (UR), the dart thrower's path (radial flexion [RF] to ulnar extension [UE]), and the anti-dart thrower's path (ulnar flexion [UF] to radial extension [RE]). The sign of the elongation rate reflects the direction of motion in which the ligament elongates (eg, a negative value in the U(+) R(−) field indicates ligament elongation in radial deviation).

*$P < .001$.

path from ulnar flexion to radial extension ($P < .001$), which is the reverse of the dart thrower's path. The DIC_S and DIC_T ligaments lengthened with elongation rates of 0.045 ± 0.008 mm/degree and 0.137 ± 0.008 mm/degree of wrist motion along the normal dart thrower's path, respectively ($P < .001$).

Anti-dart thrower's path (ulnar extension to radial flexion)

The DRC ligament lengthened with an elongation rate of 0.084 ± 0.004 mm/degree of wrist motion along the anti-dart thrower's path ($P < .001$). Fibers of the DIC ligament lengthened with elongation rates of 0.027 ± 0.004 mm/degree (DIC_S ligament) and 0.058 ± 0.004 mm/degree (DIC_T ligament) of wrist motion along a path from radial flexion to ulnar extension ($P < .001$), which is the reverse of the anti-dart thrower's path.

Paths of minimal elongation

The length of the DRC ligament remained constant along a dart thrower's path that had a coupling ratio of

1.5° of FE for every 1° of UR. The length of the DIC_S ligament was constant in pure flexion–extension, and the length of the DIC_T ligament was constant along a path, with a coupling ratio of 7.1° FE for every 1° UR.

DISCUSSION

The aim of this study was to expand our understanding of dorsal ligament function using a computational model developed with an *in vivo* carpal kinematics database. Ligaments can prevent extreme joint motion by functioning as checkreins, and they can guide the carpal bones synchronously through the wrist's full range of motion. It has been proposed that a ligament that elongates through a range of motion functions as a checkrein, whereas a ligament that does not lengthen functions as a guide.[26] Our results suggest that the dorsal carpal ligaments can function differentially, as both checkreins and guides, depending on the direction of wrist motion. In our model, the DIC ligament elongates when the wrist moves toward ulnar deviation, whereas the DRC ligament elongates when the wrist moves toward radial deviation. Accordingly, the DIC and DRC ligaments limit motion at the extremes of ulnar and radial deviation, respectively, acting as checkreins. In contrast, the elongation of the DRC ligament was minimized along a dart thrower's path that had a coupling ratio of 1.5° of FE for every 1° of UR. The length of the DIC_S ligament is essentially constant during pure wrist FE, whereas elongation of the DIC_T ligament was minimized along a path of FE and slight UR. These paths of minimal elongation would suggest that if the ligament fibers were strained, they could be functioning to guide the carpal bones through these ranges of motion.

When interpreting these data, it is important to note that the length at which a ligament transitions from being slack to generating tensile loads cannot be definitively determined with our methods. A related limitation is that slack ligament lengths were likely included in the HLM model. However, the inclusion of slack lengths in the model does not affect our elongation results because the carpal ligaments transition between slack and taut states in a linear fashion.[27] One final implication of the linear model is that a ligament fiber that elongates when the wrist is moved in a specific direction will shorten by the same amount when the wrist is moved in the exact opposite direction.

The range of elongation and the neutral length of the DIC and DRC ligaments compared well with previous *in vitro* and *in vivo* studies, despite these limitations and large variability between studies.[6,8–9,28] The neutral length of the DRC and DIC ligaments fell within ranges (14.7–17.7 mm and 13.5–40.9 mm) reported in several cadaver studies.[6,8,21] Neutral lengths and elongation of the DRC and DIC ligaments compared well with *in vivo* studies that used similar techniques to measure elongation in radial and ulnar deviation and the dart thrower's motion.[15–16] Neutral lengths of the DRC, DIC_S, and DIC_T ligaments differed between our study and previous studies by 1.0 mm, 2.8 mm, and 1.4 mm, respectively, and were within standard deviations of each other. In a cadaver study, Savelberg et al[27] injected radiopaque beads into the carpal bones and selected ligaments and performed roentgen stereophotogrammetry. They found that the DRC ligament lengthened 5.7% ± 5% when the wrist was flexed to 70° ± 15°, but it did not elongate in radial or ulnar deviation. Beginning in the clinical neutral position (0° FE and 0° UR), the elongation of the DRC ligament in our study increased to 22% (CI, 21% to 23%) in a position of 70° flexion; however, we found that the DRC ligament also elongated more substantially in positions of radial deviation. Savelberg et al reported that the DIC ligament elongated 6% ± 4% when the wrist was in 44° ± 7° ulnar deviation, but this value was not statistically significant. Our study found a greater elongation of the DIC with values of 10% (CI, 9% to 10%) (DIC_S) and 23% (CI, 23% to 23%) (DIC_T) at 40° ulnar deviation. The consistently higher elongation values found in this and other *in vivo* studies, compared to cadaver studies, could be due to the assumption that neutral length occurs at the neutral wrist position (0 ° FE and 0 ° UR). This assumption might cause higher percent changes in elongation. Although not an outcome of our study, the mean insertion site areas were within 1 standard deviation of those reported by Nagao et al[21] The average difference between insertion site areas reported by Nagao et al and those in the present study was 3 mm^2.

It has been postulated that the DRC and DIC ligaments work in tandem to support the scaphoid throughout the range of motion.[6] This is possible only if the DRC ligament is taut in the same positions that the DIC ligament is taut. Our study suggests that the ligaments might be complementary stabilizers; while one ligament is elongating, the other is shortening and possibly moving into a slack state. However, we did not model the lunate attachments of either ligament or their direct interactions with one another. Modeling these attachments might reveal an interaction between the DRC and DIC ligaments that supports the concept that they work in tandem to support the scaphoid. The DIC ligament elongated in ulnar deviation but not in FE, consistent with Macconnail's description of the screw-home mechanism of the wrist and the importance of the DIC ligament to proximal row synchrony.[29]

Our results suggest that even limited approaches to the wrist, including the dorsal approach to the scaphoid for nonunion and the triangular fibrocartilage complex approaches to the ulnocarpal joint, if associated with scarring of the dorsal extrinsic ligaments, would lead to deficits in wrist motion. A dorsal approach that leads to scarring of the DRC ligament, for example, could potentially lead to decreased wrist flexion, radial deviation, and ulnar flexion, whereas an approach that leads to scarring of the DIC ligament would lead to decreased ulnar deviation and ulnar flexion. We postulate that alternative approaches to the wrist, such as arthroscopy, that cause minimal disruption of these ligaments, along with early range of motion, might decrease the risk of postoperative wrist stiffness.

We quantified the elongation of the fibers of the DRC and DIC ligaments over all anatomical and oblique planes of active motion. Previous studies have examined length changes in these ligaments along specific motion paths. This study generated a ligament elongation model using multiple directions of wrist motion simultaneously. Computing ligament elongations as a function of wrist position is an important step toward determining the function of these ligaments during motion. We identified differing behaviors of the DRC ligament and the scaphoid and trapezoidal attachments of the DIC ligament. An improved understanding of these dynamic relationships will better predict ligament response to injury and repair and their effects on wrist range of motion.

REFERENCES

1. Berger RA, Bishop AT, Bettinger PC. New dorsal capsulotomy for the surgical exposure of the wrist. Ann Plast Surg 1995;35:54–59.
2. Hagert E, Ferreres A, Garcia-Elias M. Nerve-sparing dorsal and volar approaches to the radiocarpal joint. J Hand Surg 2010;35A: 1070–1074.
3. Berger R. The ligaments of the wrist. A current overview of anatomy with considerations of their potential functions. Hand Clin 1997;13: 63–82.
4. Taleisnik J. The ligaments of the wrist. J Hand Surg 1976;1:110–118.
5. Mitsuyasu H, Patterson RM, Shah MA, Buford WL, Iwamoto Y, Viegas SF. The role of the dorsal intercarpal ligament in dynamic and static scapholunate instability. J Hand Surg 2004;29A:279–288.
6. Viegas SF, Yamaguchi S, Boyd NL, Patterson RM. The dorsal ligaments of the wrist: anatomy, mechanical properties, and function. J Hand Surg 1999;24A:456–468.
7. Elsaidi GA, Ruch DS, Kuzma GR, Smith BP. Dorsal wrist ligament insertions stabilize the scapholunate interval: cadaver study. Clin Orthop Relat Res 2004;425:152–157.
8. Savelberg HH, Kooloos JG, Huiskes R, Kauer JM. Stiffness of the ligaments of the human wrist joint. J Biomech 1992;25:369–376.
9. Mayfield JK, Williams WJ, Erdman AG, Dahlof WJ, Wallrich MA, Kleinhenz WA, et al. Biomechanical properties of human carpal ligaments. Orthop Trans 1979;3:143–144.
10. Lacelli F, Muda A, Sconfienza LM, Schettini D, Garlaschi G, Silvestri E. High-resolution ultrasound anatomy of extrinsic carpal ligaments [in English, Italian]. Radiol Med 2008;113:504–516.
11. Smith DK. Dorsal carpal ligaments of the wrist: normal appearance on multiplanar reconstructions of three-dimensional Fourier transform MR imaging. AJR Am J Roentgenol 1993;161A:119–125.
12. Crisco JJ, Moore DC, Marai GE, Laidlaw DH, Akelman E, Weiss AP, et al. Effects of distal radius malunion on distal radioulnar joint mechanics—an *in vivo* study. J Orthop Res 2007;25:547–555.
13. Moritomo H, Murase T, Arimitsu S, Oka K, Yoshikawa H, Sugamoto K. Change in the length of the ulnocarpal ligaments during radiocarpal motion: possible impact on triangular fibrocartilage complex foveal tears. J Hand Surg 2008;33A:1278–1286.
14. Upal MA, Crisco JJ, Moore DC, Sonenblum SE, Wolfe SW. *In vivo* elongation of the palmar and dorsal scapholunate interosseous ligament. J Hand Surg 2006;31A:1326–1332.
15. Xu J, Tang JB. *In vivo* length changes of selected carpal ligaments during wrist radioulnar deviation. J Hand Surg 2009;34A:401–408.
16. Tang JB, Gu XK, Xu J, Gu JH. *In vivo* length changes of carpal ligaments of the wrist during dart-throwing motion. J Hand Surg 2011;36A:284–290.
17. Moore DC, Crisco JJ, Trafton TG, Leventhal EL. A digital database of wrist bone anatomy and carpal kinematics. J Biomech 2007;40: 2537–2542.
18. Crisco JJ, McGovern RD, Wolfe SW. Noninvasive technique for measuring *in vivo* three-dimensional carpal bone kinematics. J Orthop Res 1999;17:96–100.
19. Marai GE, Laidlaw DH, Crisco JJ. Super-resolution registration using tissue-classified distance fields. IEEE Trans Med Imaging 2006;25:1–11.
20. Sonenblum SE, Crisco JJ, Kang L, Akelman E. *In vivo* motion of the scaphotrapezio-trapezoidal (STT) joint. J Biomech 2004;37:645–652.
21. Nagao S, Patterson RM, Buford WL Jr, Andersen CR, Shah MA, Viegas SF. Three-dimensional description of ligamentous attachments around the lunate. J Hand Surg 2005;30A:685–692.
22. Nanno M, Patterson RM, Viegas SF. Three-dimensional imaging of the carpal ligaments. Hand Clin 2006;22:399–412; v.
23. Marai GE, Laidlaw DH, Demiralp C, Andrews S, Grimm CM, Crisco JJ. Estimating joint contact areas and ligament lengths from bone kinematics and surfaces. IEEE Trans Biomed Eng 2004;51: 790–799.
24. Nowalk MD, Logan SE. Distinguishing biomechanical properties of intrinsic and extrinsic human wrist ligaments. J Biomech Eng 1991; 113:85–93.
25. Littell RC, Milliken GA, Stroup WW, Wolfinger RD, Schabenberger O. SAS for mixed models. 2nd ed. Cary, NC: SAS Institute Inc, 2006.
26. Leardini A, O'Connor JJ, Catani F, Giannini S. A geometric model of the human ankle joint. J Biomech 1999;32:585–591.
27. Savelberg HH, Kooloos JG, de Lange A, Huiskes R, Kauer JM. Human carpal ligament recruitment and three-dimensional carpal motion. J Orthop Res 1991;9:693–704.
28. Nowak MD, Logan SE. Strain rate dependent permanent deformation of human wrist ligaments. Biomed Sci Instrum 1988;24:61–65.
29. Macconaill MA. The mechanical anatomy of the carpus and its bearings on some surgical problems. J Anat 1941;75:166–175.