Published in final edited form as:

J Hand Surg Am. 2020 November ; 45(11): 1012–1021. doi:10.1016/j.jhsa.2020.06.014.

In Vivo Mechanical Function of the Distal Radial Ulnar Ligaments During Rotation of the Wrist

Matthew M. Crowe, MD^{*}, John T. Martin, PhD^{*}, A. Jordan Grier, MD^{*}, Charles E. Spritzer, MD[†], Marc J. Richard, MD^{*}, David S. Ruch, MD^{*}

^{*}Department of Orthopaedic Surgery, Duke University Medical Center, Durham, NC

[†]Department of Radiology, Duke University Medical Center, Durham, NC

Abstract

Purpose—The purpose of this study was to investigate changes in length of the volar and dorsal radioulnar ligaments (VRULs and DRULs), and the distal radioulnar joint (DRUJ) space during unweighted and weighted rotation of the wrist using magnetic resonance imaging and biplanar fluoroscopy.

Methods—Fourteen wrists in 7 normal adult volunteers were imaged to define the 3-dimensional geometry of the DRUJ and the insertion sites of the superficial and deep bundles of the VRULs and DRULs. Subjects were imaged at 10 positions of forearm rotation ranging from full pronation to full supination, with or without a 5-pound weight. Lengths of the superficial and deep VRUL and DRUL bundles and DRUJ space were measured (in millimeters) at each position to evaluate ligament function and DRUJ stability.

Results—In the unweighted and weighted trials, maximal elongation of both deep and superficial VRUL bundles occurred in supination and maximal lengths of the deep and superficial DRUL bundles occurred in pronation. Maximum DRUJ space occurred during pronation and a minimum occurred in 30° of supination. In weighted trials, there was a significant increase in deep and superficial VRUL bundle length at positions between 30° of pronation and 30° of supination; however, there was no effect of weight on DRULs length. In weighted trials, there was a significant increase in DRUJ space at positions between full pronation and 15° of supination.

Conclusions—This study demonstrates elongation of the VRULs in supination and the DRULs in pronation. There was no evidence of reciprocal loading of superficial/deep ligament bundles on either the dorsal or the volar aspects of the DRUJ. The effect of loading the wrist during rotation was apparent primarily in the VRULs, but not the DRULs. The DRUJ space was lowest at approximately 30° of supination.

Clinical relevance—These results add information to the literature regarding the complicated biomechanics of the triangular fibrocartilage complex and DRUJ. Future work should evaluate changes in biomechanics caused by triangular fibrocartilage complex tears to determine how tear severity and location relate to clinical symptoms.

Corresponding author: A. Jordan Grier, MD, Department of Orthopaedic Surgery, Duke University Medical Center, 40 Duke Medicine Circle, Room 5309 (Orange Zone), Durham, NC 27710; Jordan.grier@duke.edu.

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

Keywords

Wrist; triangular fibrocartilage complex; distal radioulnar joint; biplanar fluoroscopy; 3-dimensional modeling

Ulnar-sided wrist pain remains a frequent and functionally limiting complaint after both chronic and acute injuries of the wrist. Advances in imaging and arthroscopy have shown ligamentous injury to the triangular fibrocartilage complex (TFCC) to be a major cause of ulnar-sided wrist pain.^{1,2} Despite improvements in the understanding of TFCC anatomy and function, there remains debate about the *in vivo* function of distal radial ulnar joint (DRUJ) ligaments in pronation and supination.^{3–7}

Anatomically, the TFCC is composed of the discus articularis, dorsal radioulnar ligaments (DRULs), volar radioulnar ligaments (VRULs), volar ulnocarpal ligaments, and extensor carpi ulnaris subsheath.^{8,9} The primary functions of the TFCC are transmission of compressive forces across the ulnocarpal joint during axial loading, and stabilization of the DRUJ during wrist rotation.^{10–12} The role of the TFCC in axial loading is well described because 16% to 40% of axial loads are transmitted through the TFCC depending on ulnar deviation and variance.^{13,14} During wrist rotation, however, the functions of the TFCC and specifically the VRULs and DRULs are less clearly defined because the interosseous membrane and joint capsule also play a role in rotational stability. Cadaveric studies suggest that both the VRULs and the DRULs are composed of superficial fibers that connect the radial sigmoid notch to the ulnar styloid and deep fibers, constraining the sigmoid notch to the rotational center of the distal forearm, the ulnar fovea.^{4,19–21}

A consensus has not been established in the literature regarding the relative contributions of the deep and superficial bundles of the DRULs and VRULs during wrist rotation.^{5,6,12,22} Some studies report a reciprocal function of these bundles, where in supination the superficial VRULs and deep DRULs are loaded and in pronation the superficial DRULs and deep VRULs are loaded.^{7,10} Other studies have reported no reciprocal function of the bundles, and *ex vivo* cadaveric studies suggest that the majority of DRUJ stability comes from the deep foveal fibers.^{5,12} Overall, there remain limited data on the function of these ligaments during *in vivo*, unconstrained loading conditions.⁷ A better understanding of TFCC and DRUJ function *in vivo* might refine the diagnosis of joint disease, inform surgical techniques to stabilize traumatic injuries, and ultimately improve patient outcomes.

The purpose of this study was to characterize the deformations of the superficial and deep VRUL and DRUL bundles and to measure changes in DRUJ space during wrist rotation.

MATERIALS AND METHODS

Patient selection

After institutional review board approval, 7 subjects (6 men, 1 woman; age, 24–38 years) were recruited via promotional fliers posted at our medical center and adjacent university campus. subjects consented to participate in the study after a thorough discussion regarding its relevant risks. The exclusion criteria included a history of forearm fracture or injury of

the TFCC, DRUJ, or elbow. Participants were imaged bilaterally to yield a total of 14 wrists in the study group. The study was performed at the Department of Orthopaedic surgery, Duke University Medical Center, Durham, NC.

Imaging and data processing

The wrists of all subjects were first imaged using a 3.0-T magnetic resonance imaging (MRI) (TrioTim, Siemens, Germany). Each wrist was imaged separately with the subject supine, the wrist at the subject's side, and the palm facing down in mild pronation. Images were acquired using a dedicated wrist coil (Invivo, Orlando, FL) and a coronal SPACE sequence (flip angle 40°; echo time 15 ms; repetition time 5 ms; slice thickness 0.3 mm). Stacks of MRI scans were imported into a solid modeling program (Rhino; McNeel, Seattle, WA), and radius and ulna boundaries were manually segmented to create 3-dimensional models (Fig. 1, top). For each model, the ulnar and radial attachment sites for the DRULs and VRULs were manually segmented and divided into superficial and deep bundles using an approach similar to 2 previous studies^{7,23} (Fig. 1, bottom). First, individual coordinate systems for the radius and ulna were defined for each subject. For the radius, the z axis was defined along the longitudinal axis, the y axis was defined perpendicular to the line connecting the radius sigmoid edges, and the x axis was defined perpendicular to the y and z axes in the dorsal direction. For the ulna, the z axis was defined along the longitudinal axis, the y axis was defined through the center of the ulnar styloid, and the x axis was defined perpendicular to the y and z axes in the dorsal direction. To ensure that each coordinate system was oriented consistently on both the left and the right wrist models, the left wrist models were imported to the same workspace as the right, mirrored, and an iterative closest point technique was used to align the left and right radius/ulna pairs. The right radius/ulna coordinate systems were then transferred to the left radius/ulna models. With the axes created, the ligament geometry was defined by visualizing the radial and ulnar insertion sites on the MRI scans and then the insertion boundaries were demarcated by manual segmentation. On the radial side of the DRUJ, common dorsal and common volar attachment sites were created because there was no separation between superficial and deep ligament bundles. On the ulnar side, 4 attachment sites were modeled, 1 for each bundle. The centroids of the 2 radial attachment sites and 4 ulnar attachment sites were then calculated to define the end points each ligament bundle (Fig. 1, right).

The left and right wrists of each subject were then imaged using 2 orthogonal fluoroscopes (Pulsera; Philips, The Netherlands). To do so, participants were directed to hold their elbow to their side and flexed 90°, to hold their wrist in a neutral position, and to close their hand in a fist without straining (Fig. 2, top). Subjects then rotated each wrist from a maximally supinated to a maximally pronated position and static images were recorded at regular intervals defined by a goniometer. In total, 10 positions were imaged and analyzed for each wrist (the angle of maximum pronation, 45° pronation, 30° pronation, 15° pronation, 0°, 15° supination, 30° supination, 45° supination, 60° supination, the angle of maximum supination). To simulate a load encountered during routine daily activities, subjects repeated this imaging sequence while holding a 5-pound dumbbell asymmetrically (Fig. 2, top).

Model matching and measurements

Volumetric MRI models of the radius and ulna were imported into a digital model of the laboratory and manually manipulated to match 2-dimensional projections of the 3-dimensional MRI models with the 2-dimensional biplanar fluoroscopic images (Fig. 2, bottom). The laboratory model was developed using 3 spatial calibration tools as previously described²⁴: the first to determine the position of the fluoroscopes relative to each other, a second to determine the x-ray beam centers on their opposing intensifiers, and a third to correct the intrinsic image distortion. Within this framework, the straight line distance between the modeled ligament end points and the angle of DRUJ rotation were measured. To enable comparison across subjects at exact angles of DRUJ rotation, radioulnar ligament lengths were calculated by linear interpolation at the 2 nearest DRUJ angle measurements. We also measured the DRUJ space. To do so, points on the articulating face of the radius were selected and matched with their nearest point on the ulna (Fig. 3). The average distance between matched points was calculated to determine DRUJ space at each rotation angle. We have measured the precision of each aspect of this analysis in previous studies (manual segmentation of MRI scans, 0.03 mm,²⁵ 0.04 mm²⁶; manual positioning of MRI models in biplanar fluoroscopy environment, 0.1 mm,²⁷ 0.15 mm²⁸; identifying ligament footprints, 0.3 mm,²⁹ 0.34 mm³⁰).

Statistical analysis

The VRULs length, DRULs length, and DRUJ space at each angle of wrist rotation were compared by a repeated measures analysis of variance. Fisher least significant difference post hoc test was used to determine whether differences at each position in unweighted and weighted scenarios were statistically significant with P less than .05. All values are reported as mean $\pm$ 95% confidence intervals and are included in Table E1 (available on the *Journal's* Web site at www.jhandsurg.org). A post hoc power analysis confirmed that β greater than 0.9 for the analysis of VRULs length, DRULs length, and DRUJ space.

RESULTS

The lengths of the superficial and deep VRUL and DRUL bundles were measured at each angle of DRUJ rotation (Fig. 4). Forearm rotation had a significant effect on the lengths of both the superficial and deep DRUL and VRUL bundles in both the unweighted and the weighted conditions ($P < .05$). In unweighted trials, the superficial and deep VRUL bundles followed similar trends in elongation, with a minimum length in full pronation (superficial, 11.9 ± 0.5 mm; deep, 10.3 ± 0.4 mm) and a maximum length in supination (superficial at 45° , 17.9 ± 0.4 mm; deep at 60° , 15.8 ± 0.3 mm). The DRUL bundles exhibited a reciprocal behavior to the VRUL bundles, with maximum length in 30° pronation (superficial, 15.3 ± 0.4 mm; deep, 13.4 ± 0.4 mm) and minimum length in full supination (superficial, 9.8 ± 0.5 mm; deep: 10.9 ± 0.4 mm). In the weighted trials, the superficial VRUL bundle was elongated at positions between the 45° pronation and the 30° supination in comparison to the unweighted trials (average elongation, 0.5 mm), and the deep bundle was elongated at positions between 30° pronation and 30° supination (average elongation, 0.5 mm). Conversely, the superficial and deep DRULs lengths measured during the weighted trials were not significantly different from the unweighted condition at any angle of rotation.

Rotation of the wrist caused the DRUJ space to increase in both pronation and supination, for both the unweighted and the weighted trials (Fig. 5). From the neutral position to the maximum pronation position, joint space increased, where it reached a maximum in full pronation (4.2 ± 0.2 mm). From the neutral position to the maximum supination position, joint space decreased until approximately 30° of supination where it reached a minimum (3.1 ± 0.2 mm), and then increased from 30° of supination to the maximum supination angle (at maximum supination, 3.6 ± 0.3 mm). In comparison with the unweighted trials, the measured DRUJ space during the weighted trials was significantly greater at angles between 45° pronation and 15° supination (average difference, 0.3 mm). The maximum difference in DRUJ space occurred at 30° of pronation (0.4 mm).

DISCUSSION

Ulnar-sided wrist pain remains a challenging problem to diagnose and treat despite improvements in both open and minimally invasive arthroscopic techniques. This is in part due to differing opinions regarding the biomechanical role of the specific portions of the TFCC.^{1,2,10,31,32} In this study, MRI, 3-dimensional joint modeling, and biplanar fluoroscopy were used to analyze *in vivo* VRULs and DRULs deformations during unweighted and weighted rotation of the wrist. The superficial and deep bundles of the VRULs reached maximum length at mid-supination in unweighted and weighted trials, whereas the superficial and deep bundles of the DRULs reached maximum length at mid-pronation in both trials. Because this study is one of few to evaluate *in vivo* deformations of the TFCC, it contributes valuable information on the ligamentous constraints during unconstrained rotation of the DRUJ.⁷

We defined a reciprocal function of the VRULs and DRULs, where during supination, both bundles of the VRULs are maximally elongated whereas both bundles of the DRULs are minimally elongated, and in pronation, both bundles of the VRULs are minimally elongated whereas both bundles of the DRULs are maximally elongated (Fig. 6). These findings are in conflict with the concept of reciprocal loading of deep and superficial bundles of the VRULs and DRULs described by Hagert in 1994,¹¹ who hypothesized that in supination the superficial VRULs and deep DRULs are taut, whereas in pronation the superficial DRULs and deep VRULs ligaments are taut. This concept was promoted by others, and was further elaborated upon, suggesting that superficial fibers resist extremes of rotation whereas deep bundles resist subluxation.^{10,32,33} The findings of Stuart et al¹⁵ in cadaver experiments supported that the deep bundles prevent subluxation of the DRUJ. Here, however, normal rotation of the wrist did not cause sufficient translation at the DRUJ to necessitate support of the deep bundles. That our results are in conflict with the *ex vivo* work of Stuart et al¹⁵ suggests that passive and active muscular forces present *in vivo* may contribute to DRUJ stability and affect the function of the radioulnar ligaments. Furthermore, as *ex vivo* studies demonstrated that the superficial and deep bundles of the VRULs and DRULs are loaded similarly (not reciprocally) in pronation and supination, *ex vivo* mechanical conditions must be carefully controlled to properly mimic physiological loading.^{6,34,35} The trends and magnitudes of deformation described here for the superficial VRULs and DRULs confirm the *in vivo* work of Xu and Tang.⁷ Contrary to our findings, however, Xu and Tang⁷ measured reciprocal motions in the superficial and deep bundles. In their study, the ligament

attachment sites were approximated using published histological results, whereas with our MRI method, we can directly identify ligamentous insertions on an individual-by-individual basis and account for biological variability between volunteers. This may account for the discrepancy between the results.

The effect of loading the wrist during rotation was apparent primarily in the VRULs and observed changes in DRUJ space. There were no differences in the overall shape of the length versus rotation angle curve between unweighted and weighted trials for either the VRULs or the DRULs. However, when loading the wrist, there was a significant increase in length of both VRUL bundles between 30° of pronation and 30° of supination that was not apparent in the DRULs. Other stabilizers of the DRUJ, such as the joint capsule or ulnocarpal collateral ligament, may also be resisting motions of the radius and ulna that increase dorsal DRUJ space, specifically in pronation when the DRUJ space is at its maximum. Contributions from the palmar osteocartilaginous lip, which may be present in up to 80% of individuals, may also affect volar translation of the distal ulna at positions beyond 30° of supination and, thus, have an effect on observed DRUJ space.³⁶ It has previously been observed that greater dorsopalmar translation exists during maximum isometric pronation than in maximum isometric supination (3.1 mm dorsal and 2.2 mm palmar, respectively).³⁷ Similarly, *in vivo* results put forth by Hojo et al³ demonstrate that loading of the wrist in a position of maximal pronation and hyperextension, as may be seen at the time of a fall onto an outstretched hand, results in an increase in palmar translation of the ulna compared with unweighted trials. These authors additionally noted significant elongation of both the superficial and the deep VRULs during weighted trials, with no change in either the superficial or the deep DRULs bundles, which is consistent with our findings with respect to weighted wrist rotation. Based on the results observed here, this may indicate that as the wrist moves from relative pronation to supination, the VRULs continue to elongate until maximal engagement of the ulnar head on the osteocartilaginous lip occurs. Following this maximal engagement of the ulnar head on the osteocartilaginous lip, the VRULs are no longer conferring a significant restraint to palmar translation of the ulnar head relative to that of the osteofibrocartilaginous lip and, therefore, do not further elongate. As the forearm rotation continues from 30° of supination to maximal supination, the ulnar head may remain relatively palmar while the radius continues to translate resulting in an increase in DRUJ space in maximal supination as was observed here.

In the setting of suspected DRUJ injuries with instability on examination, many patients are immobilized in near-full supination because this has been hypothesized to fully seat the ulna in the sigmoid notch of the radius and confer maximal stability to the DRUJ. However, we have demonstrated that DRUJ space is minimized at approximately 30° of supination. Because minimal joint space may be the position of maximal joint stability, immobilization of the wrist in 30° of supination following injury may confer improved stability. Further investigation is warranted to determine whether this biomechanical finding translates to a difference in clinical outcomes. Changes in mean DRUJ spacing may be attributed to gapping in one aspect of the articulation, while another aspect of the articulation remains in contact. In addition, cartilage compression, particularly in supination where the minimum DRUJ spacing was measured, may contribute to an overall decrease in joint width. These remain areas for future work.

Because muscle forces and geometric constraints likely cause stress in ligaments throughout the full range of wrist motion, it was not possible to measure the stress-free length of the VRULs and DRULs to estimate the tensile load in each. Evaluating reciprocal function as defined by the tensile forces in each ligament remains an area for future investigation. Furthermore, we measured the straight line distance between ligament insertions to determine ligament length. This provides an estimate of the true ligament length in positions when ligaments likely wrap around the radial aspect of the ulna. This represents a limitation, but likely affects only the magnitude of ligament length, not the overall trends in ligament elongation throughout wrist rotation. Although patients with a history of forearm fracture and injury of the TFCC, DRUJ, or elbow were excluded from the study, there was no formal prestudy physical examination to rule out any other subtle upper extremity pathology that may have affected the results of the study protocol completed by each participant. In addition, formal Beighton scoring for each participant was not performed prior to study inclusion. Although relatively uncommon, the presence of a connective tissue disorder may have had an impact on the results of the study performed here and future investigations should seek to control for these conditions.

In conclusion, this study presents an *in vivo* analysis of the DRUJ ligaments, directly measuring VRULs and DRULs length through the full range of forearm rotation. Our results suggest that both the superficial and the deep VRUL bundles are maximally elongated in supination whereas both bundles of the DRULs are maximally elongated in pronation. These findings conflict with the concept of the reciprocal function of the superficial and deep bundles. Loading of the wrist during rotation caused elongation of both VRUL bundles in pronation and supination, but did not affect the dorsal bundles. Furthermore, wrist loading increased the DRUJ space primarily in pronation, and only mildly in supination.

ACKNOWLEDGMENTS

The authors would like to acknowledge Louis DeF-rate, SD, Farshid Guilak, PhD, Kevin Taylor, Margaret Widmyer, W. Brad Wainright, and Gary Utturkar, MS. This study was funded in part by grants from the National Institutes of Health (F32 AR071223) and Orthopaedic Research Education Foundation (#389348394).

J.T.M.'s salary is funded by a grant from the National Institutes of Health (F32 AR071223).

REFERENCES

1. Henry MH. Management of acute triangular fibrocartilage complex injury of the wrist. *J Am Acad Orthop Surg*. 2008;16(6):320–329. [PubMed: 18524983]
2. Ruch DS, Papadonikolakis A. Arthroscopically assisted repair of peripheral triangular fibrocartilage complex tears: factors affecting outcome. *Arthroscopy*. 2005;21(9):1126–1130. [PubMed: 16171639]
3. Hojo J, Omokawa S, Iida A, Ono H, Moritomo H, Tanaka Y. Threedimensional kinematic analysis of the distal radioulnar joint in the axial-loaded extended wrist position. *J Hand Surg Am*. 2019;44(4): 336.e1–336.e6. [PubMed: 30119953]
4. Shin WJ, Kim JP, Yang HM, Lee EY, Go JH, Heo K. Topographical anatomy of the distal ulna attachment of the radioulnar ligament. *J Hand Surg Am*. 2017;42(7):517–524. [PubMed: 28450099]
5. Haugstvedt JR, Berger RA, Nakamura T, Neale P, Berglund L, An KN. Relative contributions of the ulnar attachments of the triangular fibrocartilage complex to the dynamic stability of the distal radioulnar joint. *J Hand Surg Am*. 2006;31(3):445–451. [PubMed: 16516740]

6. DiTano O, Trumble TE, Tencer AF. Biomechanical function of the distal radioulnar and ulnocarpal wrist ligaments. *J Hand Surg Am.* 2003;28(4):622–627. [PubMed: 12877850]
7. Xu J, Tang JB. *In vivo* changes in lengths of the ligaments stabilizing the distal radioulnar joint. *J Hand Surg Am.* 2009;34(1):40–45.
8. Atzei A, Luchetti R. Foveal TFCC tear classification and treatment. *Hand Clin* 2011;27(3):263–272. [PubMed: 21871349]
9. Haugstvedt JR, Langer MF, Berger RA. Distal radioulnar joint: functional anatomy, including pathomechanics. *J Hand Surg Eur Vol.* 2017;42(4):338–345. [PubMed: 28399788]
10. Kleinman WB. Stability of the distal radioulnar joint: biomechanics, pathophysiology, physical diagnosis, and restoration of function what we have learned in 25 years. *J Hand Surg Am.* 2007;32(7): 1086–1106. [PubMed: 17826566]
11. Hagert CG. Distal radius fracture and the distal radioulnar joint—anatomical considerations. *Handchir Mikrochir Plast Chir.* 1994;26(1):22–26. [PubMed: 8150382]
12. Schuind F, An KN, Berglund L, et al. The distal radioulnar ligaments: a biomechanical study. *J Hand Surg Am.* 1991;16(6): 1106–1114. [PubMed: 1748757]
13. Palmer AK, Werner FW. Biomechanics of the distal radioulnar joint. *Clin Orthop Relat Res.* 1984;187:26–35.
14. An K-N, Berger RA, Cooney WP. Biomechanics of the Wrist Joint. New York: Springer-Verlag; 1991.
15. Stuart PR, Berger RA, Linscheid RL, An KN. The dorsopalmar stability of the distal radioulnar joint. *J Hand Surg Am.* 2000;25(4): 689–699. [PubMed: 10913210]
16. Watanabe H, Berger RA, Berglund LJ, Zobitz ME, An KN. Contribution of the interosseous membrane to distal radioulnar joint constraint. *J Hand Surg Am.* 2005;30(6):1164–1171. [PubMed: 16344173]
17. Gofton WT, Gordon KD, Dunning CE, Johnson JA, King GJ. Soft-tissue stabilizers of the distal radioulnar joint: an in vitro kinematic study. *J Hand Surg Am.* 2004;29(3):423–431. [PubMed: 15140484]
18. Watanabe H, Berger RA, An KN, Berglund LJ, Zobitz ME. Stability of the distal radioulnar joint contributed by the joint capsule. *J Hand Surg Am* 2004;29(6):1114–1120.
19. Ishii S, Palmer AK, Werner FW, Short WH, Fortino MD. An anatomic study of the ligamentous structure of the triangular fibrocartilage complex. *J Hand Surg Am.* 1998;23(6):977–985. [PubMed: 9848546]
20. Nakamura T, Takayama S, Horiuchi Y, Yabe Y. Origins and insertions of the triangular fibrocartilage complex: a histological study. *J Hand Surg Br.* 2001;26(5):446–454. [PubMed: 11560427]
21. Fu E, Li G, Souer JS, et al. Elbow position affects distal radioulnar joint kinematics. *J Hand Surg Am.* 2009;34(7):1261–1268. [PubMed: 19576700]
22. Shen J, Papadonikolakis A, Garrett JP, Davis SM, Ruch DS. Ulnar positive variance as a predictor of distal radioulnar joint ligament disruption. *J Hand Surg Am.* 2005;30(6):1172–1177. [PubMed: 16344174]
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(5): 790–799. [PubMed: 15132505]
24. Englander ZA, Martin JT, Ganapathy PK, Garrett WE, DeFrate LE. Automatic registration of MRI-based joint models to high-speed biplanar radiographs for precise quantification of *in vivo* anterior cruciate ligament deformation during gait. *J Biomech.* 2018;81: 36–44. [PubMed: 30249338]
25. Coleman JL, Widmyer MR, Leddy HA, et al. Diurnal variations in articular cartilage thickness and strain in the human knee. *J Biomech.* 2013;46(3):541–547. [PubMed: 23102493]
26. Van de Velde SK, Bingham JT, Hosseini A, et al. Increased tibiofemoral cartilage contact deformation in patients with anterior cruciate ligament deficiency. *Arthritis Rheum.* 2009;60(12):3693–3702. [PubMed: 19950260]
27. Li G, Wuerz TH, DeFrate LE. Feasibility of using orthogonal fluoroscopic images to measure *in vivo* joint kinematics. *J Biomech Eng.* 2004;126(2):314–318. [PubMed: 15179865]

28. Li G, Van de Velde SK, Bingham JT. Validation of a non-invasive fluoroscopic imaging technique for the measurement of dynamic knee joint motion. *J Biomech.* 2008;41(7):1616–1622. [PubMed: 18394629]
29. Taylor KA, Cutcliffe HC, Queen RM, et al. *In vivo* measurement of ACL length and relative strain during walking. *J Biomech.* 2013;46(3):478–483. [PubMed: 23178040]
30. Abebe ES, Moorman CT III, Dziedzic TS, et al. Femoral tunnel placement during anterior cruciate ligament reconstruction: an in vivo imaging analysis comparing transtibial and 2-incision tibial tunnel independent techniques. *Am J Sports Med* 2009;37(10):1904–1911. [PubMed: 19687514]
31. McAdams TR, Swan J, Yao J. Arthroscopic treatment of triangular fibrocartilage wrist injuries in the athlete. *Am J Sports Med.* 2009;37(2):291–297. [PubMed: 19059892]
32. Szabo RM. Distal radioulnar joint instability. *J Bone Joint Surg Am.* 2006;88(4):884–894. [PubMed: 16615200]
33. Tsai PC, Paksima N. The distal radioulnar joint. *Bull NYU Hosp Jt Dis.* 2009;67(1):90–96. [PubMed: 19302063]
34. Kihara H, Short WH, Werner FW, Fortino MD, Palmer AK. The stabilizing mechanism of the distal radioulnar joint during pronation and supination. *J Hand Surg Am.* 1995;20(6): 930–936. [PubMed: 8583064]
35. Ward LD, Ambrose CG, Masson MV, Levaro F. The role of the distal radioulnar ligaments, interosseous membrane, and joint capsule in distal radioulnar joint stability. *J Hand Surg Am* 2000;25(2): 341–351. [PubMed: 10722827]
36. Tolat AR, Stanley JK, Trail IA. A cadaveric study of the anatomy and stability of the distal radioulnar joint in the coronal and transverse planes. *J Hand Surg Br.* 1996;21(5):587–594. [PubMed: 9230939]
37. Tay SC, Berger RA, Tomita K, Tan ET, Amrami KK, An KN. *In vivo* three-dimensional displacement of the distal radioulnar joint during resisted forearm rotation. *J Hand Surg Am.* 2007;32(4):450–458. [PubMed: 17398354]

FIGURE 1:

Left 3-Dimensional MRI scans were manually segmented to define the geometry of the distal radius and ulna and the insertion sites of the VRULs and DRULs. **Middle** Coordinate systems for each bone were defined using anatomical references. Ligament insertions were mapped to the bone models. **Right** After calculating centroids of the ligament insertions, a wire model was generated to define the span of the superficial and deep VRUL and DRUL bundles.

FIGURE 2:

Top Wrists were positioned within the fields of view of 2 orthogonal fluoroscopes and imaged in either unweighted or weighted conditions. **Bottom** MRI models were mapped to the fluoroscopic images to define the 3-dimensional positions of the radius and ulna. Representative image in **bottom left** pronation and **bottom right** neutral positions. The length of each ligament (blue line) was calculated in these positions.

FIGURE 3:

Identification of the DRUJ space. Points on the radial surface adjacent to the ulna were demarcated and the nearest neighbors on the ulnar surface were identified. DRUJ spacing was defined as the average distance between these points.

FIGURE 4:

Lengths of superficial and deep **left** VRUL and **right** DRUL bundles in weighted and unweighted conditions. All data points are represented as mean $\pm$ 95% confidence interval; +, $P < .1$ and *, $P < .05$.

FIGURE 5:
 DRUJ space during unweighted and weighted trials. All data points are represented as mean $\pm$ 95% confidence interval; +, $P < .1$ and *, $P < .05$.

FIGURE 6:

VRULs and DRULs tension at full supination, neutral, and full pronation positions (in reference to the minimum length of each ligament bundle measured throughout the full range of wrist motion). Superficial and deep bundles of the VRULs and DRULs have similar, not reciprocal, patterns of elongation throughout wrist rotation.

TABLE E1.

	Unweighted	Superficial VRULs Length (mm)			Deep VRULs Length (mm)			Superficial DRULs Length (mm)			Deep DRULs Length (mm)			DRUJ Spacing (mm)		
		Mean	95% CI	Mean	Mean	95% CI	Mean	Mean	95% CI	Mean	Mean	95% CI	Mean	Mean	95% CI	Mean
Supination	83	17.17	0.79	15.79	0.53	9.78	0.94	10.93	0.73	3.59	0.50					
	60	17.66	0.69	15.81	0.59	11.53	0.73	11.82	0.61	3.24	0.38					
	45	17.85	0.68	15.68	0.64	12.56	0.76	12.25	0.65	3.08	0.33					
	30	17.77	0.73	15.37	0.69	13.42	0.72	12.61	0.60	2.98	0.27					
	15	17.46	0.78	14.91	0.74	14.21	0.72	12.98	0.61	3.02	0.26					
	0	17.03	0.88	14.39	0.83	14.99	0.64	13.38	0.56	3.12	0.26					
Pronation	-15	16.21	0.93	13.73	0.89	15.17	0.69	13.41	0.57	3.54	0.34					
	-30	15.36	0.99	13.04	0.97	15.33	0.78	13.43	0.68	3.95	0.41					
	-45	14.07	0.98	12.03	0.95	15.23	0.88	13.28	0.77	4.22	0.41					
	-63	11.90	0.88	10.28	0.86	14.80	0.74	12.97	0.76	4.24	0.43					
Weighted		Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean
Supination	78	17.35	0.72	15.87	0.66	10.48	1.06	11.39	0.80	3.71	0.39					
	60	17.71	0.62	15.83	0.60	11.73	0.82	11.87	0.67	3.45	0.35					
	45	18.02	0.67	15.81	0.66	12.71	0.74	12.24	0.59	3.22	0.30					
	30	18.26	0.83	15.77	0.83	13.63	0.73	12.59	0.54	3.14	0.28					
	15	18.07	0.91	15.43	0.87	14.33	0.79	12.89	0.61	3.18	0.29					
	0	17.45	1.00	14.79	0.93	14.92	0.79	13.22	0.64	3.36	0.37					
Pronation	-15	16.85	1.02	14.29	0.96	15.20	0.76	13.28	0.64	3.82	0.50					
	-30	15.93	0.97	13.53	0.91	15.38	0.73	13.37	0.61	4.31	0.50					
	-45	14.39	1.00	12.34	0.95	15.16	0.69	13.20	0.58	4.52	0.41					
	-64	12.20	0.98	10.66	1.00	14.48	0.80	12.66	0.73	4.53	0.44					

95% CI, 95% confidence interval.