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Subject-Specific Carpal Ligament Elongation in Extreme Positions, Grip, and the Dart Thrower's Motion

This study examined whether the radiocarpal and dorsal capsular ligaments limit end-range wrist motion or remain strained during midrange wrist motion. Fibers of these ligaments were modeled in the wrists of 12 subjects over multiple wrist positions that reflect high demand tasks and the dart thrower's motion. We found that many of the volar and dorsal ligaments were within 5% of their maximum length throughout the range of wrist motion. Our finding of wrist ligament recruitment during midrange and end-range wrist motion helps to explain the complex but remarkably similar intersubject patterns of carpal motion. [DOI: 10.1115/1.4031580]

Introduction

The morphology of the carpal bones [1] and their complex system of ligaments [2] allow the wrist to maintain stability throughout a wide range of motion, despite the lack of tendon insertions on the carpal bones. The functional role of the extrinsic wrist ligaments and

their ability to regulate normal kinematics in the wrist is incompletely understood. We question whether the radiocarpal and dorsal capsular ligaments become maximally strained only at the end range of motion or remain strained throughout the entire range of motion.

It has been postulated that the carpal ligaments are slack throughout a wide range of wrist motion [3]. Using this observation and the assumption that the carpal ligaments have mechanical characteristics similar to other ligaments in the body, which function at low strains [4], researchers have assumed that the extrinsic carpal ligaments serve only as limiters of end-range wrist motion

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[3]. However, this theory has not been confirmed because there are currently no robust methods to measure strain of the intact carpal ligaments as a function of wrist position. An alternative explanation is that the carpal ligaments also exert force on individual carpal bones during midrange wrist motion. Each carpal bone is capable of six degree-of-freedom motion; therefore, these ligament forces may act to constrain and guide a bone as it moves along a specific path or directly control its direction of motion.

Engineering strain of a ligament is computed as the difference between the final length and the reference length, divided by the reference length. In order to compute actual strain, the reference length must be equivalent to the resting length, which is the length at which a ligament is no longer slack and just begins to generate tensile stress. Currently, it is not possible to determine the resting length of the intact carpal ligaments. Therefore, as a proxy for ligament strain, several studies have measured ligament elongation as function of wrist position [3,5–8]. These studies tracked the path of ligaments in in vitro cadaver studies using tantalum beads and biplanar fluoroscopy [5–7], or in vivo using a model that computes the shortest path between insertion sites with the constraint that the fibers wrap around intermediate bones [3,8]. Both types of studies measure ligament length changes of specific carpal ligaments as the wrist moves through specific paths of motion. These studies make the distinction between ligament elongation and strain because they define the reference length as the length of a ligament fiber at the neutral wrist position with unknown tensile stress, where neutral is defined as the wrist position where the long axis of the third metacarpal is aligned with the long axis of the radius.

However, there are limitations of a model that sets the reference length to the length at the neutral wrist position (neutral length). First, setting the neutral length as the reference length may result in elongation values that over- or underestimate actual strain. For example, if a ligament's fiber length is 5 mm in the neutral position and 8 mm in wrist extension, the computed elongation will be 60% in wrist extension. However, if the ligament is stiff and operates around 5% strain, the reference length should be 7.6 mm and not 5 mm. Whereas in this case, the ligament would have been slack in the neutral position. The choice of the reference length affects elongation in a nonlinear manner because as the numerator of the strain equation increases, the denominator decreases and vice versa. A related limitation is that it is difficult to target the neutral wrist position. Variability in identifying pure neutral can exceed 10 deg of flexion/extension and 10 deg radial/ulnar deviation [9,10]. This variability may introduce changes in the neutral length, which result in different elongation patterns between subjects. While the neutral length method of computing ligament elongation may help to define which wrist positions elongate a ligament, the elongation values should be interpreted with caution, as they may inflate the reported strain values in in vivo studies.

In this study, we propose an alternative method to estimate ligament strain. Rather than setting the initial state of a ligament at neutral wrist position, we assume that ligaments are relatively stiff (i.e., that they elongate only nominally at normal physiological loads) and that they reach their maximum lengths within a motion envelope that includes a wide range of extreme wrist positions. We compute the maximum length of each extrinsic wrist ligament through extremes of flexion and extension, carpal distraction, and functional tasks, and then we determine if the ligament length approaches this maximum length in midrange wrist motions or only at the end-range of wrist motion.

The purpose of this study was to model ligament function by computing ligament elongation as a function of maximum length throughout a wide range of extreme wrist positions, with the assumption that one or more of the wrist positions will strain each wrist ligament. We hypothesized that the carpal ligaments would reach 10% of their maximum lengths in midrange wrist positions.

Methods

Subjects, Imaging, and Carpal Bone Kinematics. After obtaining approval from our institutional review board and

Table 1 Database of functional tasks and dart thrower's motion ($n = 12$ subjects) with CT-scanning parameters and wrist position measured by the orientation of the third metacarpal with respect to the radius

Group	Name	Description	In-plane resolution (mm)	Slice thickness (mm)	Flexion (+), extension mean (SD)	Ulnar (+), radial deviation mean (SD)	Description of carpal bone kinematics
TASK	Neutral-grip	Forearm pronated, hand flat, gripping 28 mm diameter dowel. Light grip and with 98 N distractive load	0.3 × 0.3	0.625	−23.9 (12.5)	8.7 (6.0)	Rainbow et al. [12]
	Neutral-grip loaded				−22.0 (15.1)	5.9 (5.5)	Unpublished
	Distraction unloaded	Finger-traps, relaxed and loaded to 98 N	0.5 × 0.5	0.60	1.9 (8.2)	8.5 (5.5)	Leventhal et al. [14]
	Distraction loaded				−0.6 (3.8)	5.2 (4.4)	
	Extreme extension lightly loaded	Simulated push-up, lightly loaded and 98 N load applied			−73.9 (5.5)	11.9 (7.8)	Unpublished
	Extreme extension loaded				−78.2 (5.4)	11.3 (7.9)	Rainbow et al. [12]
DTM	Extreme flexion	Dorsum of hand flat, forced end-range flexion until slight discomfort	0.5 × 0.5	0.625	91.6 (8.2)	8.7 (5.8)	
	Hammer 1	Held wooden dowel against spokes placed at five positions that sampled hammering path from wind-up to strike			−59.6 (9.6)	−5.4 (8.9)	Leventhal et al. [15]
	Hammer 2				−48.7 (9.6)	1.5 (9.0)	and Kamal et al. [13]
	Hammer 3				−37.1 (7.9)	12.9 (9.3)	
	Hammer 4				−24.4 (7.9)	26.1 (6.5)	
	Hammer 5				−8.8 (10.7)	34.1 (5.8)

Fig. 1 Ligament fibers modeled for a representative subject's right wrist. On the volar side (left panel), the RSC was modeled with a distal (dRSC) and proximal (pRSC) fiber. The LRL was also modeled with a distal (dLRL) and proximal (pLRL) fiber. The SRL ligament was modeled with a radial fiber (rSRL), a central fiber (cSRL), and an ulnar fiber (uSRL). On the dorsal side of the wrist (right panel), the DRC ligament was modeled with a distal (dDRC) and proximal (pDRC) fiber and the DIC ligament was modeled with a distal (dDIC) and proximal (pDIC) fiber.

informed consent, we recruited six male and six female healthy, right-hand dominant volunteers as part of a larger study on the influencing of loading on carpal kinematics (age: 24.8 ± 3.8 yr). To rule out past or current wrist injury, a board-certified hand surgeon performed a wrist-directed history and physical exam, and plain radiographs were obtained. Computed tomographic (CT) scanning was performed on each of the subject's right wrists in 12 different positions; 7 that reflected high demand tasks; and 5 that captured the dart thrower's path (DTM) (a path from radial-extension to ulnar-flexion) [1,11]. We organized these 12 positions into two groups: (1) a functional-task group (TASK) that contained discrete positions of neutral-grip (unloaded and loaded), extreme extension (unloaded and loaded), extreme flexion, carpal distraction (unloaded and loaded), and (2) five incremental positions along the DTM. Details of these positions and the resulting carpal kinematics were previously reported (Table 1) [14,15].

Briefly, neutral-grip was acquired as volunteers lightly held a plastic dowel, and while they resisted a distally directed load of 98 N that was applied to the dowel. Two positions of extreme extension were acquired as the volunteers simulated a push-up position by placing the palm of their hand against a vertical plate and applying no load and a load of 98 N. In extreme loaded flexion, volunteers were asked to place the dorsal aspect of their hand flat against a vertical plate and fully flex their wrist until they felt resistance. Unloaded distraction was acquired with finger-traps affixed to the volunteer's fingers while they were lying prone, with the palm of their hand pressed flat to the scanner bed. Loaded distraction was acquired by applying a tensile load of 98 N to the finger traps. Finally, five positions along the path of a simulated hammering task were collected as the volunteers held a dowel against five equally spaced stops arrayed along a hammering arc. Three-dimensional carpal bone surface models and six degrees-

Fig. 2 Ligament fibers of a representative subject's right wrist in each TASK position. The color of each ligament fiber correlates to its length as a function of the maximum length or R_p value, averaged across all subjects. Blue fibers represent R_p values below 90%, green fibers represent R_p values greater than or equal to 90% and less than 95%, and the R_p value of red fibers is 95% or higher. Unloaded grip and unloaded extension are not shown because they were similar to loaded grip and loaded extension, respectively; therefore, the images are representative of both loading conditions.

of-free kinematics of all eight carpal bones, radius, and ulna, and all five metacarpals were obtained using a previously established markerless bone segmentation and registration technique from the acquired CT volume images [2,16].

Ligament Modeling. Boundaries of insertion of the radioscaphocapitate (RSC), long radiolunate (LRL), dorsal radiocarpal (DRC), dorsal intercarpal (DIC), and short radiolunate (SRL) ligaments were manually mapped onto each subject's bone surface models in Geomagic (Raindrop Geomagic, Durham, NC). Published anatomical descriptions guided the mapping process [17–19]. The RSC, LRL, DRC, and DIC ligaments were modeled with two fibers placed at the most proximal and distal aspects of their respective regions of insertion. Due to its broad attachment, the SRL ligament was modeled with three fibers arranged from radial to ulnar (Fig. 1). We determined fiber length l_p at each wrist position by computing the shortest path from the origin of the ligament to its insertion with the constraint that the bone surface models were not penetrated [20].

Estimating Ligament Fiber Recruitment. Our analysis assumed that each fiber achieves its maximum length $l_{\max}$ in at least one of the 12 wrist positions examined in this study. The elongation, E_p of each fiber at each position, p throughout the remaining positions was computed as a function its length, l_p , and the maximum length, $l_{\max}$

$$E_p = \frac{l_p}{l_{\max}} \quad (1)$$

The recruitment at each position (R_p) was defined as

$$R_p = 100 * E_p \quad (2)$$

R_p is thus defined as a measure of ligament length and we note that when R_p is equal to 100%, the fiber's length is equal to $l_{\max}$.

Statistical Analysis. For each ligament, a mixed linear model determined whether R_p varied as a function of wrist position or fiber. Fiber and posture were included as fixed factors and subject was included as a random factor in the model. Both TASK and DTM groups were pooled in this analysis. We performed a subanalysis on the DTM positions to determine whether R_p varied as a

function of path (radial-extension to ulnar flexion). This was done by performing linear regression on R_p as a function of the angle along the DTM. We tested whether the slope of the regression line was significantly different than zero using an F -test ($\alpha = 0.05$).

Results

The mixed linear model revealed that R_p varied as a function of wrist posture ($p < 0.001$) (Figs. 2 and 3). R_p also varied among fibers within the RSC, LRL, SRL, and DRC ($p < 0.001$). In contrast, there was no detectable difference in R_p between fibers within the DIC ($p = 0.2$). The position where fiber length was maximized ($l_{\max}$) varied as a function of fiber, subject, and posture (Table 2). Differences within each ligament are described below.

RSC. Both representative fibers (distal (d) and proximal (p)) of the RSC approached their maximum lengths in extreme loaded extension with R_p values for the dRSC and pRSC of $97.3 \pm 2.3\%$ and $99.5 \pm 1.4\%$, respectively (Figs. 4(a) and 4(b)). During the DTM, from radial extension to ulnar flexion, the R_p values of the dRSC increased ($p < 0.001$) from 93.8 ± 2.1 to $98.6 \pm 1.1\%$, with the maximum fiber length being reached in 8 out of 12 subjects during one of the DTM positions (Table 2). In contrast, the length of the pRSC remained relatively constant ($p = 0.4$) at an R_p of $93.2 \pm 3.1\%$ throughout the DTM (Figs. 4(c) and 4(d)).

LRL. In the TASK group, the R_p value of the dLRL was 95% or higher in all positions but in loaded distraction ($90.2 \pm 7.6\%$) and extreme flexion ($83.9 \pm 5.2\%$). The pLRL had the highest R_p values during neutral-grip ($94.9 \pm 5.0\%$) and extreme extension ($98.4 \pm 2.2\%$). Both fibers of the LRL had the lowest R_p values in extreme flexion. Interestingly, loaded distraction also decreased the R_p value of the dLRL and pLRL to $90.2 \pm 7.6\%$ and $83.4 \pm 9.3\%$, respectively (Figs. 5(a) and 5(b)), as the lunate moved distally and radially with wrist distraction. During the DTM, the mean R_p value of the dLRL increased ($p < 0.001$) from $96.1 \pm 2.9\%$ to $99.5 \pm 1.0\%$, but the length of the pLRL remained nearly constant ($p = 0.4$) at an R_p value of $96.9 \pm 3.2\%$ (Figs. 5(c) and 5(d)).

SRL. Extreme extension elongated the rSRL, cSRL, and uSRL to $l_{\max}$ in at 8 out of 12 subjects for the rSRL and 11 out of 12 subjects for the cSRL and uSRL (Table 2 and Figs. 6(a)–6(c)) in the

Fig. 3 Ligament fibers of a representative subject's right wrist moving through the DTM. The color of each ligament fiber correlates to its length as a function of the maximum length or R_p value, averaged across all subjects. Blue fibers represent R_p values below 90%, green fibers represent R_p values greater than or equal to 90% and less than 95%, and the R_p value of red fibers is 95% or higher. From left to right, the wrist moves from radial-extension in the first hammering position (H1) toward ulnar flexion in the final hammering position (H5).

TASK group. During the DTM, from radial extension to ulnar flexion, the R_P value of the rSRL increased from $86.5 \pm 5.6\%$ to 96.5 ± 3.6 , the cSRL remained constant with an R_P value of $91.6 \pm 4.8\%$, and the R_P of the uSRL decreased from $95.8 \pm 2.9\%$ to $92.5 \pm 4.4\%$ (Figs. 6(d)–6(f)).

DRC. The dDRC was elongated in extreme flexion ($99.7 \pm 0.4\%$) as evidenced by 9 out of 12 subjects reaching $l_{\max}$ in this position (Table 2). The R_P value of the dDRC was greater than 95% in neutral-grip and unloaded distraction. The pDRC behaved similarly to the dDRC. However, the R_P value was greatest in unloaded distraction ($97.3 \pm 2.8\%$), neutral-grip ($97.4 \pm 3.5\%$), and extreme flexion ($96.7 \pm 3.4\%$) (Figs. 7(a) and 7(b)). Both representative fibers of the DRC decreased ($p < 0.001$) as the subject's wrists were moved through different positions along the DTM (Figs. 7(c) and 7(d)).

DIC. The R_P value of the DIC was greatest in neutral-grip ($97.5 \pm 1.7\%$), unloaded distraction ($96.7 \pm 2.4\%$), and through positions along the DTM. The R_P value of the pDIC was between $94.5 \pm 2.8\%$ and $97.7 \pm 2.0\%$ for all positions within TASK, except loaded distraction where R_P was $90.9 \pm 4.9\%$ (Figs. 8(a) and 8(b)). The lengths of both fibers of the DIC increased as the

wrist moved along the DTM ranging from R_P values of $95.1 \pm 2.9\%$ in the first hammering position to R_P values of $99.4 \pm 0.7\%$ in the final position (Figs. 8(c) and 8(d)). The pDIC reached its maximum length during one of the DTM positions in 7 out of 12 subjects. The dDICs in all 12 subjects reached their maximum lengths during one of the DTM positions.

Discussion

In this study, we explored the question of whether carpal ligaments support the wrist in midrange-of-motion wrist positions or if they acted only as check-reins at extreme range-of-motion positions [3]. Our results indicate that the extrinsic carpal ligaments operate within 5% elongation relative to the maximum length during midrange as well as end-range wrist motion. This implies that the ligaments are taut and exert forces on the carpal bones that support them throughout midrange wrist motion and also limit end-range wrist motion. With the exception of the DIC, we also found differential behavior within an individual ligament depending on its fiber location. This finding supports the proposition that the carpal ligaments (not unlike the cruciate ligaments of the knee [21]) are a confluence of tissues and that different regions within a given ligament are differentially strained depending on the direction of joint motion [7].

Fig. 4 Elongation of the RSC ligament. The dashed lines represent R_P values of 90% and 95%. (U) and (L) denote unloaded and loaded conditions, respectively. Top: R_P values of the distal (a) and proximal (b) fibers of the RSC for all subjects within the TASK group. Bottom: elongation of the distal (c) and proximal (d) fibers of the RSC during the DTM. Each line represents a subject's elongation pattern. The symbol of each line is consistent across all figures. The solid black line represents a regression line that was fit to elongation as a function of DTM across all subjects. The R^2 value of the regression line is included in the figure followed by an indication of whether the slope was significantly different than zero (* = significant: $p < 0.05$, NS = not significant). The RSC was elongated maximally during extreme extension. During the DTM, fibers of the dRSC also approached their maximum lengths as the wrist rotated from the neutral (0 deg) toward ulnar flexion.

Our approach differs from the previous carpal ligament elongation studies because the analysis does not assume that the neutral position is the resting length. Engineering strain ε is defined as

$$\varepsilon = \frac{l_p - l_0}{l_0}$$

where l_0 is the length at which a ligament fiber begins to undergo strain and produces a tensile force. Previous *in vivo* studies of ligament elongation are unable to determine the resting length and typically replace l_0 by the length at the neutral wrist position. By computing the maximum fiber length and assuming that a stiff ligament will only elongate slightly once it is strained within the range of physiologic motion, our analysis avoids the variability inherent in using the neutral wrist position to define l_0 .

To interpret our data, we assumed that there is a high probability that a ligament is strained when it is within 95% of its maximum length. We further assumed that the each ligament reached its maximum length in at least 1 of the 12 wrist positions we measured. We think that this is a reasonable assumption, given that our dataset included extreme positions in multiple directions of motion. As the ligament fiber lengths decreased below 95% of their maximum length, we also reasoned that the likelihood that they are strained decreases and the likelihood that they are slackened increases [22]. Our method is a refinement in that it models

the general behavior of the carpal ligaments using accurate *in vivo* kinematics and a robust fiber-wrapping algorithm that mimics the course of the physical ligaments.

There is substantial variability in the reported stiffness and strain values reported among mechanical studies of the carpal ligaments [23–28]. For example, one study measured the stiffness of the scapholunate interosseous ligament to be 66 N/mm [26], while another measured 250 N/mm [25]. Likewise, failure strains of the extrinsic ligaments range from 20% to 50% between studies [25,28], and failure strains of the interosseous ligaments are reported to be as high as 200% [28]. These values are much higher than those reported for other skeletal ligaments. For example, ligaments in the knee fail at 12–15% strain [4]. Aside from the inherent difficulty in identifying and isolating the carpal ligaments, differences in displacement rates, the definition of resting length (l_0), and differences in testing protocols undoubtedly underlie the lack of consensus. Since the carpal ligaments are organized similar to ligaments in other joints, we postulated they would be strained in an operating range similar to other ligaments ($\sim 5\%$). Our results support this hypothesis. If the carpal ligaments are more compliant, as suggested by Nowalk and Logan, the range of motion that the ligaments support would increase, which would not conflict with our conclusions. This is intuitive, as is exemplified by the increased wrist range of motion in patients with collagen vascular disorders, such as Ehlers Danlos or Marfan diseases.

Fig. 5 Elongation of the LRL. The R_p value (left y-axis) is the percentage of $\varepsilon_{\max}$ (right y-axis). Top: elongation of the distal (a) and proximal (b) fibers of the LRL for all subjects within the TASK group. Bottom: elongation of the distal (c) and proximal (d) fibers of the LRL during the DTM. With the exception of loaded distraction and extreme flexion, the LRL was elongated within 95% of its maximum length throughout the entire range of motion.

Table 2 For each ligament (columns), the number of subjects (total $n = 12$) whose fibers reached maximum length $l_{\max}$ in a given wrist position (rows). With the exception of the SRL, the prefix of each ligament stands for d = distal and p = proximal. The prefix for the SRL stands for r = radial, c = central, and u = ulnar.

		Ligament										
Group	Wrist position	dRSC	pRSC	dLRL	pLRL	rSRL	cSRL	uSRL	dDRC	pDRC	dDIC	pDIC
TASK	Neutral-grip								1	1		
	Neutral-grip loaded	3		1	3					4		3
	Distraction unloaded								2	2		
	Distraction loaded		1							1		
	Extreme extension lightly loaded	1	1		1	1	2	2				1
	Extreme extension loaded		9		3	7	9	9				
	Extreme flexion								9	4		
DTM	Hammer 1	1		1	1		1	1				1
	Hammer 2				1							
	Hammer 3	1	1	1							1	1
	Hammer 4	5		1		1					3	5
	Hammer 5	1		8	3	3					8	1

Clinical Correlations: The RSC Ligament. The RSC ligament has been suggested to act as a secondary constraint to radio-carpal pronation or ulnar translocation and as a stabilizer of the distal pole of the scaphoid [17]. Cadaveric and in vivo studies consistently report that the RSC elongates from the neutral position to ulnar deviation and from neutral to extension [8,29–32]. There are divergent reports on the elongation of the RSC in radial deviation with some studies reporting elongation [5,31,32], some reporting shortening [3,30], and others reporting minimal length changes [7]. In agreement with Tang et al. [8], our results indicate that the RSC is maximally elongated in extreme extension. A recent study reported that the RSC decreased to 90% as the wrist moved from neutral into ulnar flexion along the DTM [8]. Our results differ, suggesting that the RSC elongates through a large range of the DTM and increases maximally as the wrist ulnar

flexes. The RSC may potentially serve as a stabilizer to the carpus as it moves into ulnar deviation or toward ulnar flexion [17]. It is important to note, however, that despite a change of approximately 50 deg from extension toward flexion, the wrist was in slight extension during the final DTM position (Table 1). Differences in elongation of the RSC in the present study compared to previous work can be explained by different coupling ratios of flexion to ulnar deviation. The average coupling ratio of the present study was 1.14 ± 0.43 deg of flexion for every 1 deg of ulnar deviation, while the previous study had a coupling ratio of approximately 3 deg of flexion for every 1 deg of ulnar deviation [8].

The LRL Ligament. The LRL ligament is separated from the RSC by the interligamentous sulcus and does not extend to the

Fig. 6 Elongation of the SRL ligament. The R_p value (left y-axis) is the percentage of $l_{\max}$ (right y-axis). Top: elongation of the radial (a), central (b), and ulnar (c) fibers of the SRL for all subjects within the TASK group. Bottom: elongation of the radial (d), central (e), and ulnar (f) fibers of the SRL during the DTM. With the exception of loaded distraction and extreme flexion, the LRL was elongated within 95% of its maximum length throughout the entire range of motion.

distal carpal row. It has been suggested that the LRL primarily prevents ulnar and distal translation of the lunate while not interfering with flexion and extension [17]. However, studies consistently report elongation of the LRL with wrist extension [5,7,30,31], suggesting the LRL restrains lunate extension. Our results are in agreement with these reports. Previous in vitro studies using differential displacement transducers found that the LRL also elongates with wrist radial deviation [31,32]. In contrast, a cadaveric study that tracked implanted tantalum beads with stereoradiography found that while the proximal fibers remained unchanged, the distal fibers increased in length with ulnar deviation [7]. An in vivo study that used similar methods as ours showed an increase of approximately 20% from neutral to ulnar deviation [3]. Our results suggest that fibers of the LRL elongate similarly to the RSC but are generally closer to their maximum fiber lengths. Savelberg et al. found that the LRL significantly elongated in ulnar deviation [7]. We found that the LRL behaved in the DTM similar to Savelberg et al.'s findings during ulnar deviation. We found that throughout the DTM, the proximal fiber remained at a constant length, while the distal fiber increased with increasing ulnar flexion. Additionally, our results suggest that the LRL restrains the lunate from tilting during neutral-grip. Both the LRL and RSC must be maintained to prevent ulnar translocation of the carpus following scaphoid excision and four-corner-fusion [33]. The functional role of both the LRL and RSC was analyzed in a cadaveric model and demonstrated that excessive radial styloidectomy can be associated with division of the LRL and RSC and result in ulnar and palmar wrist instability. Our results

corroborate what is seen clinically, as both of these ligaments are oriented such that they prevent ulnar translation of the lunate during ulnar deviation. They are also elongated (along with the SRL) during extreme wrist extension, likely stabilizing the lunate.

The SRL Ligament. Berger [34] first identified the SRL ligament and proposed that it may restrain wrist flexion and extension, influence lunate kinematics, and prevent distraction of the lunate. Berger later suggested that some part of the SRL ligament may be under tension throughout the range of wrist motion [17]. The present study provides the first description of the in vivo elongation of the SRL. Our results suggest that the SRL restricts the lunate in extension but not in flexion. The radial, central, and ulnar fibers of the fan-shaped SRL elongate differentially during the DTM. The radial fibers appear to limit range of motion at the end of the DTM (ulnar deviation and slight extension), while the most ulnar fibers restrict the lunate in radial-extension. It is interesting to note that in one subject, the transition from hammer position 2 to hammer position 3 was associated with more wrist flexion than ulnar deviation; therefore, the lunate in this subject flexed more compared to other subjects and the SRL shortened (Fig. 6—pink trace, solid triangles).

During carpal distraction, the lunate translated distally less than half the amount of the scaphoid [12], suggesting that the lunate was more restricted. However, it did not appear that the SRL was responsible for limiting translation of the lunate because it did not elongate from unloaded to loaded distraction. We propose that the

Fig. 7 Elongation of the DRC ligament. The R_p value (left y-axis) is the percentage of s_{max} (right y-axis). Top: elongation of the distal (a) and proximal (b) fibers of the DRC for all subjects within the TASK group. Bottom: elongation of the distal (c) and proximal (d) fibers of the DRC during the DTM. The DRC was elongated within 95% of its maximum length during grip, extreme flexion, and unloaded distraction. The DRC decreased as the wrist moved along the DTM.

translation of the lunate is not limited in distraction by the SRL because the lunate is not directly connected to the distal row; therefore, the distractive forces are transferred obliquely to the direction of loading through the scapholunate, lunotriquetral interosseous, and DIC ligaments. The SRL elongates during extreme wrist extension to help stabilize the lunate. Based on these findings, we speculate that any scarring of the SRL, such as might occur with wrist trauma, may be a source of wrist extension loss.

The DRC Ligament. The DRC was originally described as thin and weak compared to its volar counterparts [2]. It was more recently proposed to play a stabilizing role during force application while the wrist is in the neutral position [5]. Cadaveric studies of DRC elongation patterns report that it shortens from neutral to wrist extension and remains constant or decreases from neutral to ulnar and radial deviation [5,7]. A recent in vivo study reported elongation of the DRC in radial deviation [35]. Our results confirm that the DRC is lengthened during unloaded distraction (similar to clinical neutral) and neutral-grip, but also during extreme flexion. Additionally, the DRC appears to be tensioned at the beginning of the DTM, when the wrist is in radial extension. Cadaveric analysis of the DRC ligament has shown that it reinforces the lunotriquetral interosseous ligament and prevents static volar intercalary segmental instability in the setting of lunotriquetral ligament tears [36,37]. We postulate that because the DRC is elongated in extreme flexion, it may help to restrain dorsal translation of the radiocarpal joint.

The DIC Ligament. Viegas et al. emphasized the importance of the DIC ligament in maintaining normal carpal posture and normal carpal kinematics [23]. Deep fibers of the DIC ligament insert on the dorsal scapholunate interosseous ligament and may act as a labrum to the scapho-capitolunate “acetabulum” of the midcarpal joint. Berger suggested it may serve to constrain midcarpal motion [17]. An in vivo study of DIC elongation found that the scaphoid attachment of the DIC elongates up to 12% from neutral to ulnar deviation [3]. We found that as a result of the narrowing of the carpus during loaded distraction [14], the DIC shortened. The DIC ligament was elongated most during neutral-grip and unloaded distraction and through a large range of the DTM. Previously, Macconnaill proposed the screw-home theory of the wrist which states that the DIC is crucial for proximal row synchrony, tightening during wrist flexion and radial deviation [38]. Recently, Mitsuyasu et al. provided some evidence for this, showing that the DIC ligament serves to support the scaphoid and lunate articulation and prevents static scapholunate instability in the presence of a scapholunate interosseous ligament tear [39]. Our results suggest that the DIC may function to stabilize the radiocarpal and midcarpal joints during grip and through the DTM. We have also recently shown that the DIC ligament serves to support the midcarpal joint and the lunate from increased lunate extension after distal scaphoid excision [40]. While both the DRC and DIC remained elongated during wrist flexion, which includes motion of both the radiocarpal and midcarpal joints, only the DIC remained elongated during the DTM, where motion predominantly occurs at the

Fig. 8 Elongation of the DIC. The R_p value (left y-axis) is the percentage of ϵ_{max} (right y-axis). Top: elongation of the distal (a) and proximal (b) fibers of the DIC for all subjects within the TASK group. Bottom: elongation of the distal (c) and proximal (d) fibers of the DIC during the DTM. With the exception of unloaded distraction, the DIC was elongated within 94% throughout the range of motion.

midcarpal joint. Interestingly, elongation of the DIC during the DTM mirrored elongation of the distal fibers of the LRL and RSC, while the DRC decreased. These observations highlight how the DICs static tension throughout complex coupled functional motions, like the dart throw, underscores its critical importance to carpal row synchrony and kinematics.

This study computed in vivo carpal ligament elongations throughout a large range of functional and extreme wrist postures. We examined elongation utilizing maximal elongation and an assumption of maximum strain to compute the reference length rather than using length in the neutral wrist position as the reference length. While our approach could not yield actual in vivo ligament strain values, it uniquely allowed us to explore the potential that the carpal ligaments provide restraint at end-range as well as midrange motion. Our results largely agreed with previous ligament elongation studies, suggesting that in addition to limiting end range of motion in multiple directions of wrist motion, the extrinsic radiocarpal and dorsal capsular ligaments are taut and exert force on individual bones of the carpus through midrange wrist motion. Whether these ligament forces act to constrain and guide a bone as it moves along a specific path or directly control its direction of motion cannot be answered with these methods. Studies of ligament elongation throughout the normal range of wrist motion highlight the importance of the extrinsic carpal ligaments to normal wrist function and give insight into pathologic carpal kinematics and potential surgical interventions.

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Nomenclature

DIC = dorsal intercarpal
DRC = dorsal radiocarpal
 E_p = ligament fiber elongation in a given wrist position
 $l_{\max}$ = maximum ligament length across wrist positions
 l_p = ligament fiber length in a given wrist position
LRL = long radiolunate
 R_p = ligament length as a percentage of maximum strain
RSC = radioscapophcapitate
SRL = short radiolunate

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