Macroscopic and Microscopic Analysis of the Thumb Carpometacarpal Ligaments

A Cadaveric Study of Ligament Anatomy and Histology

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Background: Stability and mobility represent the paradoxical demands of the human thumb carpometacarpal joint, yet the structural origin of each functional demand is poorly defined. As many as sixteen and as few as four ligaments have been described as primary stabilizers, but controversy exists as to which ligaments are most important. We hypothesized that a comparative macroscopic and microscopic analysis of the ligaments of the thumb carpometacarpal joint would further define their role in joint stability.

Methods: Thirty cadaveric hands (ten fresh-frozen and twenty embalmed) from nineteen cadavers (eight female and eleven male; average age at the time of death, seventy-six years) were dissected, and the supporting ligaments of the thumb carpometacarpal joint were identified. Ligament width, length, and thickness were recorded for morphometric analysis and were compared with use of the Student t test. The dorsal and volar ligaments were excised from the fresh-frozen specimens and were stained with use of a triple-staining immunofluorescent technique and underwent semi-quantitative analysis of sensory innervation; half of these specimens were additionally analyzed for histomorphometric data. Mixed-effects linear regression was used to estimate differences between ligaments.

Results: Seven principal ligaments of the thumb carpometacarpal joint were identified: three dorsal deltoid-shaped ligaments (dorsal radial, dorsal central, posterior oblique), two volar ligaments (anterior oblique and ulnar collateral), and two ulnar ligaments (dorsal trapeziometacarpal and intermetacarpal). The dorsal ligaments were significantly thicker ($p < 0.001$) than the volar ligaments, with a significantly greater cellularity and greater sensory innervation compared with the anterior oblique ligament ($p < 0.001$). The anterior oblique ligament was consistently a thin structure with a histologic appearance of capsular tissue with low cellularity.

Conclusions: The dorsal deltoid ligament complex is uniformly stout and robust; this ligament complex is the thickest morphometrically, has the highest cellularity histologically, and shows the greatest degree of sensory nerve endings. The hypocellular anterior oblique ligament is thin, is variable in its location, and is more structurally consistent with a capsular structure than a proper ligament.

Clinical Relevance: Delineation of the structural and microscopic anatomy of the ligaments of the thumb carpometacarpal joint provides further evidence regarding the stability and mobility of this joint that is often affected by osteoarthritis.

The enigmatic anatomy and function of the thumb carpometacarpal joint is a crucible of study, with its unique concavoconvex shape, complex joint biomechanics, and prevalence of pathology[1-4]. Gray described this biaxial "saddle-joint" as an "articulation by reciprocal reception."[5] The metacarpal moves on the trapezium in the motion arcs of flexion-extension and adduction-abduction, with wide circumduction similar to both ball-and-socket and condyloid joints, despite different configurations (Fig. 1)[5].

Stability and mobility represent the paradoxical demands of the thumb carpometacarpal joint, yet the structural origin of these functions is poorly defined. Anatomic dissections and

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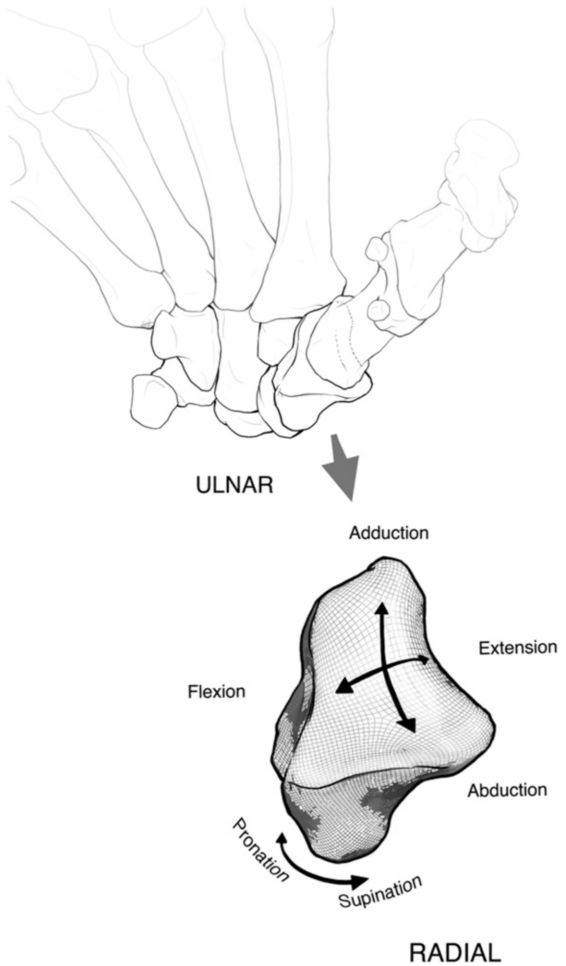

Fig. 1
Diagrams showing the topography of the distal trapezial joint surface, as redrawn from computed tomography (CT) surface rendering of a normal right hand. The thumb carpometacarpal joint motion arcs of the metacarpal on the trapezium are flexion-extension and abduction-adduction. Pronation-supination represents composite rotation and translation of this joint based on morphology and muscular activity. The thumb position in relation to the fingers represents a completion of the carpal arch, which places the thumb carpometacarpal joint oblique to the adjacent fingers. The arcs of motion thus are out of phase with the fingers, depending on the thumb's position in space.

cadaveric biomechanical studies have variably described the role of minimally constrained osseous architecture, intrinsic and extrinsic capsular ligaments, and a musculotendinous envelope as contributors to static and dynamic stability[6,7].

Studies have described between three and sixteen ligaments supporting the thumb carpometacarpal joint[1,8-11]. Controversy exists as to the primary thumb carpometacarpal joint stabilizers for both ligament identification and nomenclature. The volar ligaments, specifically the anterior oblique ligament (also referred to as the volar beak ligament[12]), predominate in the literature as the primary stabilizers, but the intermetacarpal ligament and the dorsal ligaments have also been named[13,14]. We are aware of only one study that has examined the relationship between the macroscopic appearance and microscopic composition of the anterior oblique ligament[15]. To our knowledge, there have been no studies comparing the macroscopic and microscopic structure of the greater ligament complex, including the relationship of capsule to ligament, and structural content of collagen content and cellularity. Furthermore, studies of dynamic stability, which investigate ligament sensory innervation, proprioception, and neuromuscular control, have been performed on the knee, shoulder, ankle, and wrist, but such studies on the thumb carpometacarpal joint are lacking[16-20].

We hypothesized that a comparative macroscopic and microscopic analysis of the ligaments of the thumb carpometacarpal joint would further define their role as stabilizers of this complex joint and performed a morphometric analysis of ligament location and dimensions to compare the histological and neuromorphometric characteristics of the ligaments.

Materials and Methods

Specimens

Ten fresh-frozen and twenty-five embalmed cadaveric hands were dissected; five of the embalmed specimens were excluded because of extensive osteophyte formation disrupting the integrity of the enveloping ligaments. The thirty remaining hands represented nineteen adult cadavers (eight female and eleven male) with an average age at the time of death of seventy-six years (range, forty-three to ninety-nine years; the age at the time of death was unknown for four cadavers). Dissection included the identification of commonly reported ligaments as well as their sites of attachment and orientation. The volar and dorsal ligaments were selected for additional histological analysis as these ligaments have been repeatedly named as the primary stabilizers of the thumb carpometacarpal joint[8-10]. Consequently, the dorsal radial ligament, the dorsal central ligament, the posterior oblique ligament, the anterior oblique ligament, and the ulnar collateral ligament were harvested from each of the ten fresh-frozen hands from eight cadavers (three female and five male) with a mean age at the time of death of sixty-five years (range, fifty-three to seventy-four years; the age at the time of death was unknown for two specimens). Only the fresh-frozen specimens were available for further histological analysis as immunofluorescence is generally considered to be unreliable for the evaluation of embalmed tissue because of possible impairment or blocking of antigen activity[21]. Each ligament was excised at the insertion into bone and was suture-marked for proximal-distal orientation.

Approval for this project was granted through the local institutional review board, and the handling of human remains adhered to ethical and practical protocols.

Dissection Techniques and Measurements

The dissections were performed by two experienced hand surgeons with use of loupe magnification (3.5× and 4.5×) and standard hand surgical instruments. Soft tissues were excised over the first and second metacarpals, the first and second carpometacarpal joints, and the scaphotrapeziotrapezoid joint; the nerve branches to the dorsal and volar thumb carpometacarpal joint capsule were noted. Only the abductor pollicis longus tendon was left attached to the first metacarpal. The thenar muscles were elevated in a proximal-distal direction to reveal the underlying joint capsule. At the level of the thumb carpometacarpal joint capsule, we used the wrist ligament identification technique described by Berger and performed meticulous dissection to reveal the ligaments enveloping the thumb carpometacarpal joint[22,23]. Ligaments were identified as "longitudinal groupings of collagen fibers, so called fascicles," with an "epiligamentous sheath" encountered at the interface of the "fibrous and synovial strata, converg[ing] to virtually encapsulate the ligament."[23] This isolation defines, according to Berger, "a specific ligament from contiguous ligaments, the joint space and extracapsular structures."[23] Such identification of epiligamentous sheaths in this study revealed seven specific ligaments as stabilizers of the thumb carpometacarpal joint.

With use of a digital caliper with 0.02-mm accuracy, all ligaments were measured in a position of maximum passive tension as described by Bettinger et al. to allow for consistent description of length, width, and thickness[10]. To further ensure representative measurements, each dimension was measured three times and the arithmetic mean was used as the specimen's final value. These final values were averaged over all specimens to calculate the mean and range of ligament dimensions. Using manually applied passive tension, a method previously employed by authors who have historically identified the "stabilizing role" of ligaments[10,12], also allowed for study of the passive restraint characteristics of the ligaments. Last, a dorsal or volar arthrotomy was performed to allow study of the remaining intra-articular structures.

Macroscopic Assessment of Joint Surfaces

The joint surfaces were examined in all ten fresh-frozen and twenty-five embalmed specimens. We excluded five embalmed specimens from the study because of disruption of the enveloping ligaments and the presence of global eburnation and joint dysmorphology. Preservation of the trapezial saddle configuration and absence of osteophytes confirmed the relative "normal" physiologic state of the joint, even in the presence of grade-0 or I changes as described by Outerbridge[24], in twenty-two of the remaining thirty specimens.

Histology and Immunohistochemistry

Harvested ligaments from all ten fresh-frozen specimens (fifty specimens total) were immediately fixed in 4% formaldehyde, embedded in paraffin, and then sectioned at a thickness of 8 μm before being mounted on glass slides. A standard immunohistochemical protocol was followed, and a combination of dual and triple-staining techniques was performed to validate our findings of sensory nerve endings in the carpometacarpal ligaments, both of which were described in detail in a recent publication[25]. Briefly, three primary antibodies were used: anti-nerve growth factor receptor p75 (p75), anti-Protein Gene Product 9.5 (PGP9.5), and anti-S100 (S100) antibody (Millipore, Billerica, Massachusetts). Alexa Fluor 488 and 647 (Invitrogen, Carlsbad, California) were used for the secondary antibodies. ProLong Gold Anti-Fade Reagent with 4′,6′-diamidino-2-phenylindole (DAPI) (Invitrogen) was used concomitantly to highlight DNA material in specimens.

The immunohistochemical sections were imaged with use of a fluorescence microscope (Observer.Z1, Carl Zeiss MicroImaging, Thornwood, New York), with a multidimensional acquisition setting being used to analyze sensory nerve endings with use of wavelength settings of 358, 488, and 596 nm to maximize portrayal of immunofluorescent details[25].

For histomorphometric analysis, twelve representative sample areas measuring 320.32 mm^2 (208 ×154 μm) were selected from each of the five ligaments from the ten fresh-frozen specimens and were photographed at the DAPI wavelength (358 nm), and the numbers of nuclei were counted.

Ordinal Analysis of Innervation

An ordinal grading system previously used for analysis of ligament innervation was employed to quantify the degree of innervation and to assess for mechanoreceptor presence[20,26]. The grading system ranged from (+++) to (−), with (+++) representing the presence of several nerve fascicles and mechanoreceptors, (++) representing the presence of a single nerve fascicle and receptor, (+) representing the presence of nerve fascicles but no receptors, and (−) representing the presence of no nerve fibers, fascicles, or mechanoreceptors.

Statistical Analysis

For the morphometric analysis, possible significant ($p < 0.05$) differences in the mean values of ligament length, width, or thickness were compared with use of the Student t test for independent variables. For the histomorphometric analysis, mixed-effects linear regression was used to estimate the cell-count differences between ligaments while accounting for dependencies in the data, with three measurements being obtained per ligament in each of the five ligaments per specimen. Mixed-effects linear regression was also used to estimate the differences in innervation grade between ligaments while accounting for dependencies in the data, obtaining two locations per ligament, in each of the five ligaments per specimen. From this model, simultaneous pairwise comparisons were made between the ligaments, with a family-wise 95% confidence level, producing estimates, Z-statistics, p values, and simultaneous 95% confidence intervals for the mean differences between each ligament pair. This model was elaborated to estimate the effect of location (proximal versus distal) as well as an interaction term to evaluate if the effect of location varied by ligament.

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Results

Ligament Anatomy

We identified seven principal ligaments; three capsular ligaments, defined with use of the technique of Berger[23],

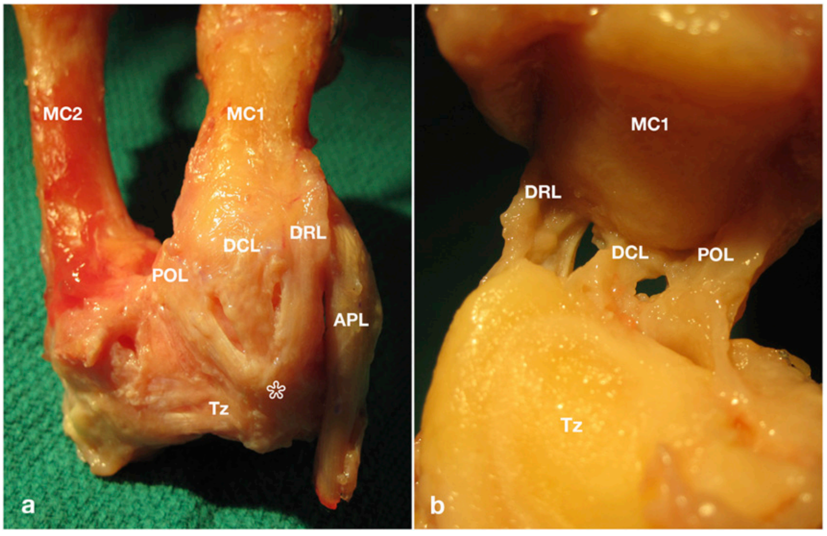

Fig. 2
Photographs showing the dorsal thumb carpometacarpal ligaments as seen from the dorsal aspect of the thumb (**Fig. 2-A**) and from a volar view within the joint (**Fig. 2-B**), illustrating the three ligaments of the stout dorsal deltoid ligament complex, including the dorsal radial ligament (DRL), the dorsal central ligament (DCL), and the posterior oblique ligament (POL). The deltoid ligament complex emanates from the tubercle (*) of the dorsal trapezium (Tz) and inserts fan-shaped onto the dorsal base of the first metacarpal (MC1). Also seen is the insertion of the abductor pollicis longus (APL) and the dorsal aspect of the second metacarpal (MC2).

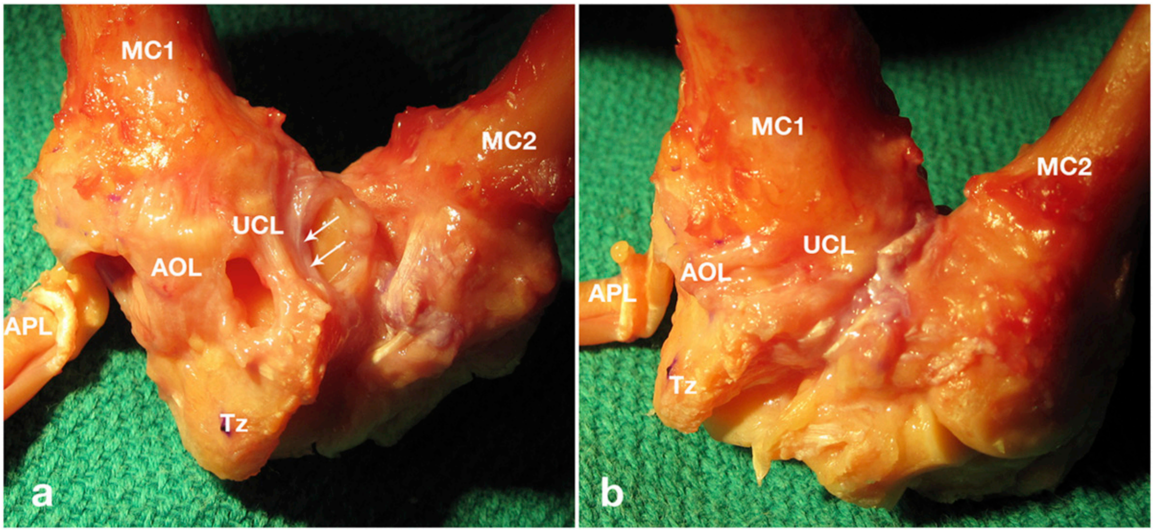

Fig. 3

Photographs showing the thin volar ligaments of the thumb carpometacarpal joint. The diaphanous anterior oblique ligament (AOL) and ulnar collateral ligament (UCL) (also known as the first volar trapeziometacarpal ligament [VTM-1]) are noted with the thumb carpometacarpal joint in extension (**Fig. 3-A**) and flexion (**Fig. 3-B**). The abductor pollicis longus (APL) is reflected distally. In this specimen, a capsular structure seen deep to the ulnar collateral ligament is interpreted as the deep anterior oblique (arrows). Tz = trapezium, MC1 = first metacarpal, and MC2 = second metacarpal.

spanned the dorsal thumb carpometacarpal joint: (1) the dorsal radial ligament, (2) the dorsal central ligament, and (3) the posterior oblique ligament. Two volar ligaments were identified: (1) the anterior oblique and (2) the ulnar collateral ligament. Two ulnar ligaments were identified: (1) the first dorsal trapeziometacarpal ligament and (2) the intermetacarpal ligament. All seven ligaments were consistently found in all thirty specimens. The location, orientation, and average dimensions of each ligament, including standard deviations, are listed in Table I.

Dorsal Ligaments—Deltoid Ligament Complex

Three capsular ligaments enveloped the dorsal thumb carpometacarpal joint. These ligaments emanated from the dorsal tubercle on the trapezium and fanned out to insert onto the first metacarpal in a deltoid appearance. We designated these three ligaments (the dorsal radial ligament, dorsal central ligament, and posterior oblique ligament) as the deltoid ligament complex (Fig. 2).

The dorsal radial ligament emanated from the radial aspect of the dorsal tubercle of the trapezium, coursed slightly obliquely, and inserted onto the dorsoradial side of the first metacarpal. The primary insertion of the abductor pollicis longus overlay the majority of this ligament.

We consistently identified the dorsal central ligament using Berger's technique[23], located and delineated between the dorsal radial ligament and posterior oblique ligament; this has not previously been described in the literature. This ligament originated on the center of the dorsal tubercle of the trapezium, with longitudinally oriented fibers that inserted onto the central dorsal edge of the first metacarpal providing the central limb of the deltoid ligament complex. The dorsal central ligament was the shortest and thickest of the ligaments stabilizing the thumb carpometacarpal joint.

The posterior oblique ligament originated from the ulnar side of the dorsal tubercle of the trapezium and coursed obliquely and ulnarly to insert ulnarly on the first metacarpal, corresponding to the insertion site of the first dorsal interosseous muscle on the first metacarpal. The posterior oblique ligament

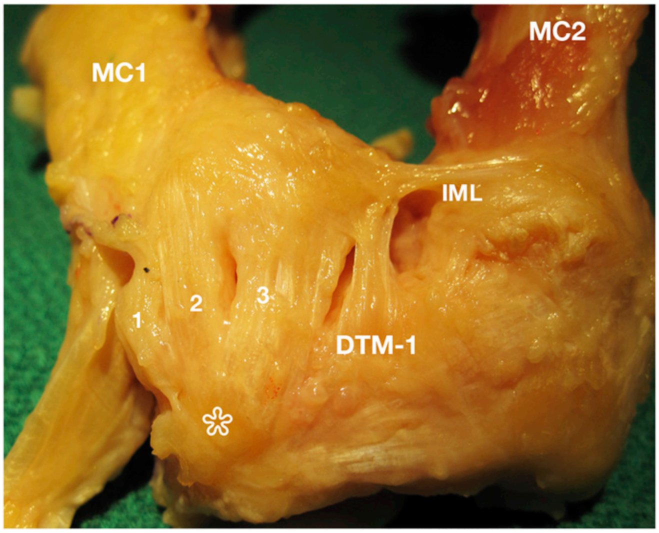

Fig. 4

Photograph showing the ulnar thumb carpometacarpal ligaments from the dorsal view, with the thumb in abduction. The first dorsal trapeziometacarpal ligament (DTM-1) stabilizes the thumb carpometacarpal joint in abduction, pronation, and flexion, whereas the intermetacarpal ligament (IML) stabilizes the joint in abduction and supination. The dorsal deltoid ligament complex is also seen in this view (1, 2, and 3). * = dorsal tubercle of the trapezium, 1 = dorsal radial ligament, 2 = dorsal central ligament, 3 = posterior oblique ligament, MC1 first metacarpal, and MC2 = second metacarpal.

was the longest ligament supporting the thumb carpometacarpal joint, with the broadest insertion onto the first metacarpal.

When passive, manual force was applied to the thumb, the deltoid ligaments were maximally taut in a position of flexion and visually appeared to prevent dorsal subluxation of first metacarpal. The deltoid ligament complex consistently had the stoutest ligaments of all thumb carpometacarpal joint-stabilizing ligaments, with a significant difference in thickness compared with the volar and ulnar ligaments ($p < 0.05$).

Volar Ligaments

Careful attention was paid to the dissection of the volar ligaments of the thumb carpometacarpal joint, given the reported variability of their location[1,10,12]. Visualization required elevation of the thenar muscles, which, in all specimens, were intimal to the volar joint capsule. This capsule was uniformly thin and fragile with consistent openings, independent of the presence or absence of joint chondromalacia. Two fibrous structures were found at the volar thumb carpometacarpal joint: the anterior oblique ligament and the ulnar collateral ligament (Fig. 3).

The anterior oblique consistently originated on the volar edge of the trapezium. Its insertion accompanied the variable volar abductor pollicis longus insertion onto the first metacarpal but always inserted ulnar to the abductor pollicis longus, most frequently onto the volar distal extension of the metacarpal, the "beak." In all specimens, the anterior oblique was extremely thin and capsular. With an average thickness of <0.8 mm, this diaphanous structure was hard to delineate even with 3.5× to 4.5× loupe magnification and macroscopically appeared to be little more than reinforced joint capsule. Two previous studies have demonstrated the existence of a superficial and a deep anterior oblique[10,12]. In our dissections, we consistently found one thin "ligament," maximally taut in a position of passive thumb extension and adduction. In only three of the thirty specimens could a capsular structure be seen to lie deep to the ulnar collateral ligament when the joint was observed from without and within, possibly denoting the deep anterior oblique as described by Bettinger et al.[10].

Unlike the other ligaments described above, the ulnar collateral ligament was an extracapsular ligament[13,27] originating

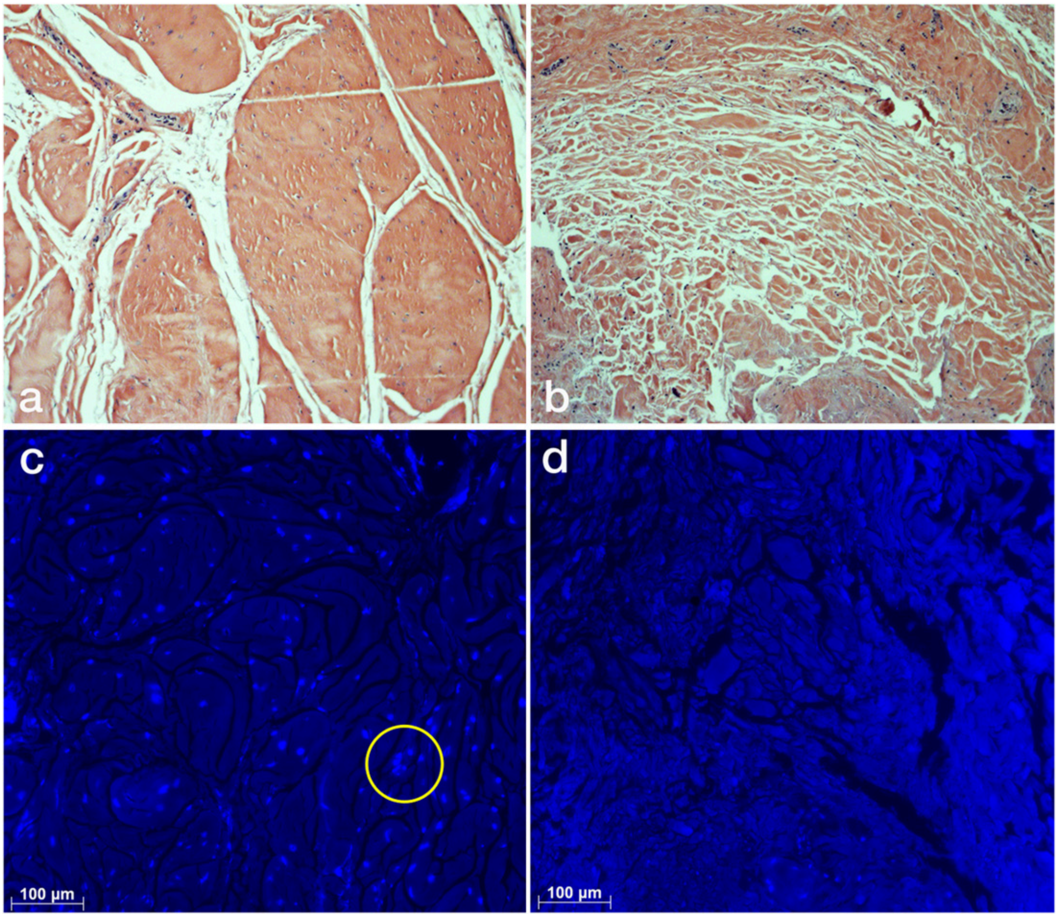

Fig. 5

Histological appearance of the dorsal radial ligament (**Figs. 5-A and 5-C**) and the anterior oblique ligament (**Figs. 5-B and 5-D**) as stained with hematoxylin and eosin (**Figs. 5-A and 5-B**) and DAPI (**Figs. 5-C and 5-D**). The dorsal radial ligament demonstrates distinct collagen bundles with both stains, with the nuclei of the fibrocytes in the collagen visualized with DAPI (**Fig. 5-C**); the circle indicates a cluster of nuclei. In contrast, the anterior oblique ligament has the appearance of disorganized connective tissue, with no apparent collagenous structure (**Fig. 5-B**) or cellularity (**Fig. 5-D**).

TABLE I Ligament Dimensions*

Ligament	Length *(mm)*	Width *(mm)*	Thickness *(mm)*
DRL	9.75 ± 0.81	5.00 ± 0.61	1.86 ± 0.12
DCL	9.18 ± 1.29	4.92 ± 0.25	1.95 ± 0.14
POL	13.03 ± 1.58	5.95 ± 0.40	1.71 ± 0.22
AOL	9.38 ± 0.61	4.68 ± 0.52	0.71 ± 0.11
UCL	9.36 ± 0.60	4.27 ± 0.26	0.98 ± 0.14
DTM-1	9.58 ± 0.59	3.80 ± 0.53	1.10 ± 0.09
IML	10.29 ± 0.75	2.20 ± 0.39	0.79 ± 0.09

*The values are given as the mean and the standard deviation. DRL = dorsal radial ligament, DCL = dorsal central ligament, POL = posterior oblique ligament, AOL = anterior oblique ligament, UCL = ulnar collateral ligament, DTM-1 = first dorsal trapeziometacarpal ligament, and IML = intermetacarpal ligament.

primarily from the distal edge of the transverse carpal ligament inserting onto the volar ulnar ridge of the trapezium. The fibers coursed slightly obliquely to insert onto the volar ulnar first metacarpal. A more anatomic name for this ligament, and complementary to its dorsal counterpart, is the first volar trapeziometacarpal ligament. The ulnar collateral ligament/first volar trapeziometacarpal ligament was maximally taut when the thumb was passively positioned in extension and abduction.

Ulnar Ligaments

The ulnar ligaments, namely, the first dorsal trapeziometacarpal ligament and the intermetacarpal ligament, supported the thumb carpometacarpal joint on its ulnar side (Fig. 4). The ulnar collateral ligament/first volar trapeziometacarpal ligament technically falls into this category but was categorized as a volar ligament (as described above) for historical consistency.

The first dorsal trapeziometacarpal ligament originated on the dorsal ulnar edge of the trapezium and coursed obliquely to insert primarily next to the posterior oblique ligament insertion but also onto the ulnar volar edge where the ulnar collateral ligament inserted. The first dorsal trapeziometacarpal ligament may be seen as the dorsal counterpart to the ulnar collateral ligament/first volar trapeziometacarpal ligament as they were both taut in passive thumb abduction and pronation.

The intermetacarpal ligament has been described to consist of dorsal and volar portions with variable presence[1,10]. In our dissections, however, the intermetacarpal ligament was consistently present as one ligament, always originating from

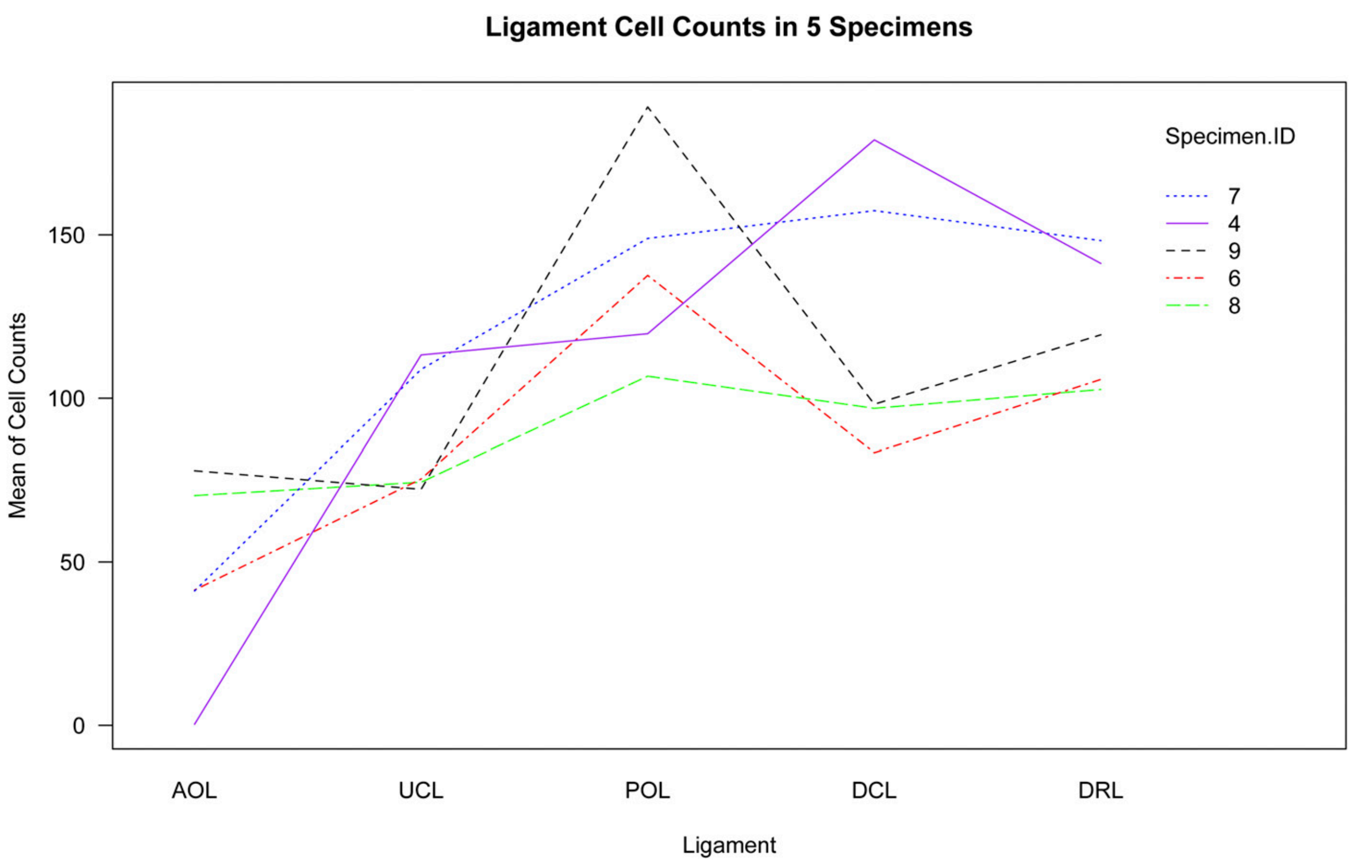

Fig. 6
Line graph showing the distribution of mean ligament cell counts in each of the five carpometacarpal ligaments from five specimens. AOL = anterior oblique ligament, UCL = ulnar collateral ligament, POL = posterior oblique ligament, DCL = dorsal central ligament, DRL = dorsal radial ligament.

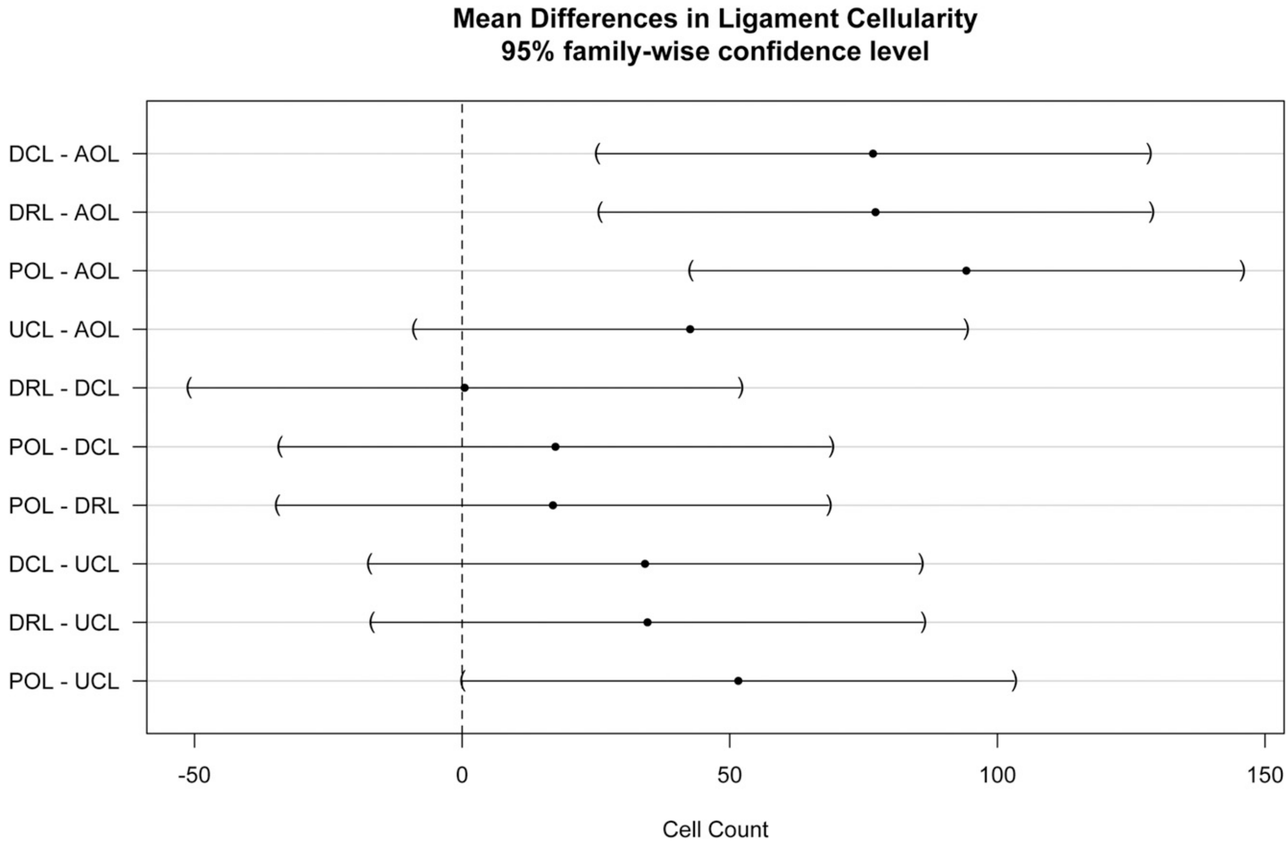

Fig. 7

Mixed-effects linear regression with simultaneous pairwise comparisons of the mean differences in ligament cellularity between the five carpometacarpal ligaments. The dorsal radial ligament (DRL), dorsal central ligament (DCL), and posterior oblique ligament (POL) were significantly ($p < 0.05$) more cellular than the anterior oblique ligament (AOL). In addition, the posterior oblique ligament was found to be significantly more cellular ($p < 0.05$) than the ulnar collateral ligament (UCL).

the dorsal radial edge of the second metacarpal and inserting onto the volar ulnar first metacarpal. It was a thin, extracapsular ligament that was passively taut in the extremes of abduction.

Histological and Histomorphometric Findings

Hematoxylin and eosin staining demonstrated the composition of the dorsal and volar ligaments. Uniformly, the dorsal radial ligament, dorsal central ligament, posterior oblique ligament, and ulnar collateral ligament consisted of organized collagen bundles with collinear orientation. The anterior oblique, however, consisted of disorganized connective tissue with sparse presence of collagen fibers and an appearance resembling synovial tissue. The difference in both ligament organization and ligament cellularity was additionally observed on a DAPI stain, with the nuclei of the organized collagen being seen in the dorsal ligaments but not in the disorganized connective tissue of the anterior oblique (Fig. 5). This lack of organization and cellularity supported our inability to identify a true macroscopic ligament presence according to the Berger technique[23].

The distribution of cell counts in each of the five ligaments from five fresh-frozen cadaver specimens is illustrated in Figure 6. Comparative analysis of the histomorphometric results between each ligament (Fig. 7) revealed a significantly greater degree of cellularity in each of the dorsal ligaments as compared with the anterior oblique ($p < 0.05$ for dorsal radial ligament versus anterior oblique, dorsal central ligament versus anterior oblique, and posterior oblique ligament versus anterior oblique). In addition, the posterior oblique ligament was more cellular than the ulnar collateral ligament/first volar trapeziometacarpal ligament. There was no significant difference when comparing the dorsal radial ligament and dorsal central ligament with the ulnar collateral ligament/first volar trapeziometacarpal ligament ($p > 0.1$). There was also no significant difference when comparing cellularity within the dorsal ligaments ($p = 0.88$ to 1.0) or within the volar ligaments ($p > 0.1$).

Pattern of Innervation Distribution Within and Between Ligaments

Mechanoreceptors and nerve fibers were generally found in the ligament epifascicular layers, close to arterioles, and with greater abundance close to the ligament insertion into bone (Fig. 8). Significant differences were observed when the degree

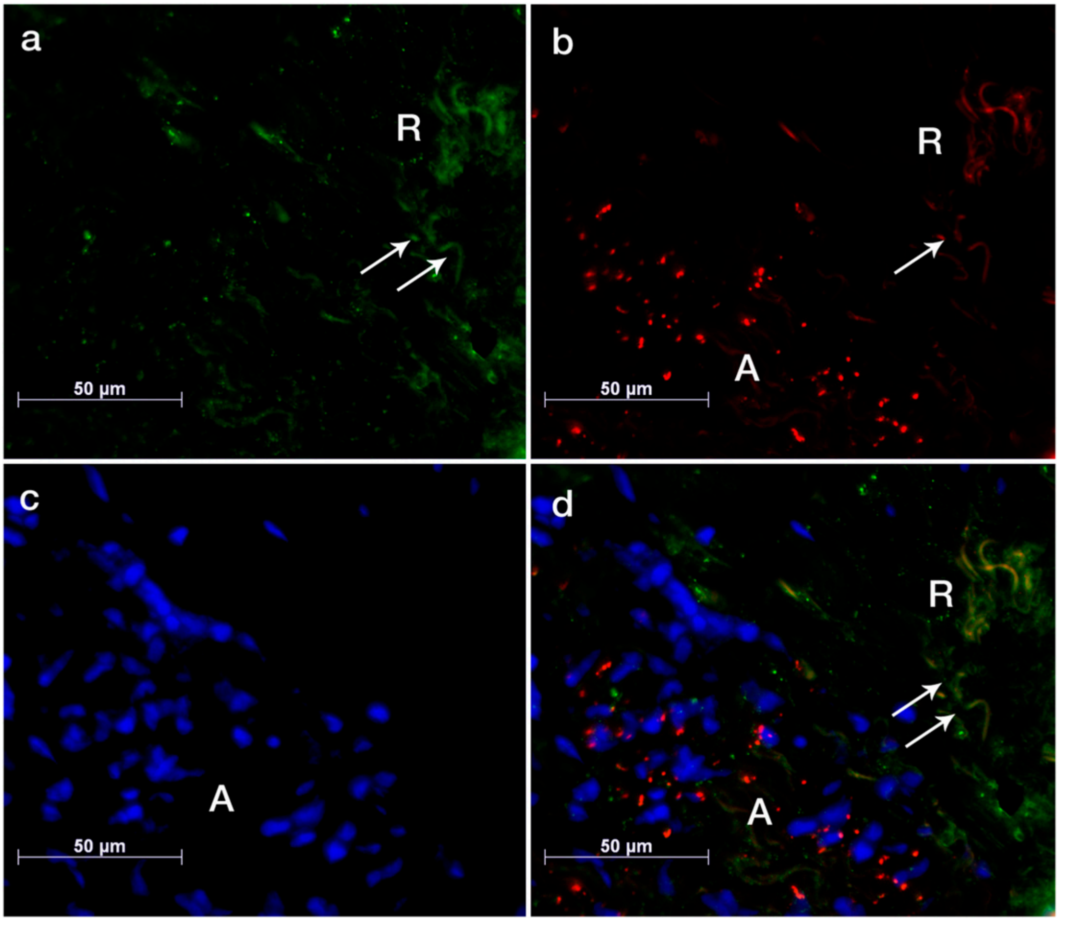

Fig. 8

Overview of the ligament composition in a dorsal radial ligament sample as seen with use of a triple-staining immunofluorescence technique. A mechanoreceptor (R) with distinct p75 immunofluorescence (**Fig. 8-A**) and PGP9.5 immunofluorescence (**Fig. 8-B**) is seen in close proximity to the arteriole. The parent axon (arrows) is seen leading up to the receptor (**Figs. 8-A and 8-B**). A large arteriole (**Fig. 8-A**) is identified with the DAPI stain (**Fig. 8-C**), and the innervation in the vessel wall shows PGP9.5 immunofluorescence (**Fig. 8-B**). The last image (**Fig. 8-D**) shows the p75, PGP9.5, and DAPI stains imaged simultaneously for a coherent understanding of the ligament topography. Median nerve specimens at the wrist level from two hands were used for control.

of innervation was compared between the distal and proximal portions of each ligament ($p < 0.05$), with a greater number of nerve endings in the distal first metacarpal insertion than the proximal trapezial origin.

When the three dorsal ligaments were compared with the two volar ligaments as a group, there was a significantly greater distribution of nerve endings in the dorsal ligaments ($p < 0.001$). There was no significant difference when the degree of innervation was compared within the dorsal or volar ligaments ($p > 0.1$).

Discussion

This descriptive, semiquantitative study analyzed the anatomical, histological, histomorphometric, and sensory characteristics of the ligaments of the thumb carpometacarpal joint and thus further defined the role of ligaments as restraints and stabilizers by both confirming and refuting the findings of previous studies. Previous reports have described as few as three and as many as sixteen ligaments stabilizing the thumb carpometacarpal joint[10,11]. We consistently observed seven ligaments that stabilized the thumb carpometacarpal joint: three dorsal ligaments (dorsal radial ligament, dorsal central ligament, posterior oblique ligament), two volar ligaments (anterior oblique, ulnar collateral ligament/first volar trapeziometacarpal ligament), and two ulnar ligaments (intermetacarpal ligament, first dorsal trapeziometacarpal ligament).

We found a previously undescribed dorsal central ligament, which, together with the dorsal radial ligament and the posterior oblique ligament, created a dorsal deltoid ligament complex, consistent in its location and orientation. This complex was uniformly stout and robust, with the thickest ligaments morphometrically, the highest cellularity histologically, and the greatest degree of sensory nerve endings. Our morphometric findings of the dorsal radial ligament and posterior oblique ligament corresponded with those of Bettinger et al.[10] and also with those of studies on stability of the thumb carpometacarpal joint following ligament sectioning, purporting the dorsal radial ligament to be of primary importance[28,29]. Previous studies on the innervation patterns of wrist ligaments have demonstrated differences in the degree of innervation, denoting a potential difference in ligament function[20,26], with richly innervated ligaments believed to have a role in neuromuscular and proprioceptive function of a joint[30] in addition to providing static joint stability. Greater innervation in the dorsal as compared with the volar ligaments additionally supports the importance of the dorsal ligaments as stabilizers of the thumb carpometacarpal joint, both from a sensory perspective and from a biomechanical perspective.

The most controversial finding of our study was related to the anterior oblique ligament. The anterior oblique has been named in many previous publications[1,9-13,26,31-33], but the description of and importance assigned to this structure have varied greatly. Haines and Van Brenk et al. described the anterior oblique as a volar ligament inserting ulnarly on the first metacarpal[1,29], whereas Pellegrini described an insertion onto the beak[12]. Napier described an anterior ligament as part of three ligaments stabilizing the joint (lateral, posterior, anterior) but offered no description of its exact anatomic position or function[11]. Pieron described the anterior oblique as a "curtain-like" structure covering the volar joint surface[33]. Bettinger et al. divided the anterior oblique into superficial and deep portions[10], with the former corresponding to a thin capsular structure and the latter corresponding to an intra-articular ligament, the "beak" ligament as described by Pellegrini[12]. While all authors have described a general "anterior oblique," to our knowledge, only two studies have demonstrated the deep "beak" ligament, which has been assigned an importance in joint stability[10,12].

In our study, the anterior oblique was consistently a thin, diaphanous structure with variable insertion and was difficult to delineate from the volar capsule. Histologically and histomorphometrically, the anterior oblique corresponded to a disorganized, hypocellular structure rather than a true ligament capable of static joint stability; this harkens to Berger's reclassification of the radioscapholunate "ligament of Testut," after both careful dissection and histological evaluation, to be a neurovascular structure[22,34,35]. Our findings refute the primary importance of the anterior oblique and support previous biomechanical investigations demonstrating that the anterior oblique is "highly compliant and would therefore function as a poor stabilizer [since] a compliant ligament would allow continuous subluxation and therefore instability."[36] Our description of the anterior oblique is thus in agreement with Pellegrini's 1991 original description of a "large anterior or subthenar capsule," which is "a voluminous pouch accommodating metacarpal translation during palmar adduction and abduction. . . Excision of this redundant capsular segment. . .had no effect on trapeziometacarpal joint stability."[12]

When the volar ligaments were analyzed from within the joint, we rarely (in three of thirty specimens) found a capsular structure located deep to the ulnar collateral ligament/first volar trapeziometacarpal ligament, which may correspond to the so-called "deep anterior oblique." This finding concurs with the description of the deep anterior oblique as reported by Pellegrini[12], who called this the "volar beak ligament," which was seen only from within the joint and only in specimens without advanced arthritic changes[12]. On the basis of this description, Bettinger et al. found the deep anterior oblique in 70% of their specimens[10] but provided no information on whether the presence of the deep anterior oblique was related to articular changes of the joint; in fact, that study provided no information regarding the articular status of the cadaveric specimens. In our review of the literature on thumb ligament anatomy[1,9-13,27,31-33], we were unable to find additional studies accurately defining or verifying the existence of the deep anterior oblique. Thus, we suggest that the anterior oblique, both deep and superficial, should be reclassified as a volar capsular complex.

In both the Bettinger and Pellegrini studies[10,12], the function of the deep anterior oblique was evaluated with use of subjective manual testing of ligament lengthening and tension following passive loading. Pellegrini described the deep anterior oblique as important for preventing dorsal subluxation of the joint and stabilizing in thumb pronation[12], whereas Bettinger et al. described its importance in preventing ulnar subluxation and stabilizing in abduction as well as pronation[10]. A recent, novel, in vivo computed tomography study on length changes of ligaments stabilizing the thumb carpometacarpal joint, determined by identifying the reported location of ligaments with use of a subtraction technique of joint position[37], was not able to confirm these functions. Instead, the anterior oblique shortened in every thumb position analyzed (flexion, abduction, opposition), denoting ligament laxity, whereas the dorsal radial ligament consistently and significantly ($p < 0.05$) lengthened in the same positions. The authors concluded that the dorsal ligament has a critical role, and the beak ligament a lesser function, in stability of the thumb carpometacarpal joint[37].

Limitations of the Study

Although our study was a multilayered analysis, it was a semiquantitative descriptive study of the anatomy and histology of the ligaments of the thumb carpometacarpal joint. In addition to the nature of descriptive studies, it had several additional limitations. Our specimens were from donors who had a relatively high mean age at the time of death, and the donors were predominately male. We recognize that it would have been favorable to do a comparative study on younger specimens with an equal male:female ratio. The average age of the donors at the time of death (seventy-six years), however, was comparable with those in the studies by Pellegrini[12] and Bettinger et al.[10] (seventy-nine and seventy-three years, respectively).The degeneration or morphological change of thumb carpometacarpal joint ligaments accompanying typical osteoarthritis and pathological chondromalacia of this joint was not examined because it was beyond the scope of the study, which was aimed at refining the description and definition of normal structures.

In concordance with the literature on the anatomy of the thumb carpometacarpal joint, we relied on the evaluation of cadaveric tissue, mostly embalmed tissue, to provide evidence by inference of the functional role that these ligaments perform; this is an obvious limitation of the present study. Manually applied passive force to test ligament function, although a crude method of assessment, was used as it has been the method of choice in previous publications on the function and anatomy of the ligaments of the thumb carpometacarpal joint[9,10,12]. True biomechanical studies to test ligament integrity and thereby infer stability in functional tasks, as well as the evaluation of live study subjects to assess dynamic stability, would provide the most evidence to the stabilizing role of the ligaments of the thumb carpometacarpal joint. The limitation of our ligament sampling was the inclusion of only dorsal and volar ligaments, thus excluding the intermetacarpal ligament, which has been previously described as an important stabilizer of this joint[9,10,12]. The limitations of our immunofluorescent analysis included the use of fresh-frozen specimens as fresh specimens are considered more reliable. However, as we consistently found nerve endings in the dorsal ligaments, we believe that our specimens represented adequate sampling quality. To strengthen our methodology, we devised a new triple-staining immunofluorescent technique, which enhanced our ability to accurately depict and differentiate between sensory nerve endings and minimized the potential for photobleaching[25].

Finally, the ordinal grading of nerve endings and the lack of power analysis is a limitation of the present study. A precise quantification would have required sectioning and staining at every 8-μm interval in all specimens, followed by z-stack mapping in a confocal microscope[38]. Technical limitations precluded this refinement. However, we used a previously published scale that provides a semi-quantitative description of the innervation pattern in ligaments[20,26,39]. The statistical analysis performed in collaboration with our departmental statistician established the congruent approach to data interpretation. ■

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