Three-dimensional analysis of elbow soft tissue footprints and anatomy

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\textbf{Background:} Tendinous and ligamentous injuries commonly occur in the elbow. This study characterized the location, surface areas, and origin and insertional footprints of major elbow capsuloligamentous and tendinous structures in relation to bony landmarks with the use of a precision 3-dimensional modeling system.

\textbf{Methods:} Nine unpaired cadaveric elbow specimens were dissected and mounted on a custom jig. Mapping of the medial collateral ligament (MCL), lateral ulnar collateral ligament (LUCL), triceps, biceps, brachialis, and capsular reflections was then performed with 3-dimensional digitizing technology. The location, surface areas, and footprints of the soft tissues were calculated.

\textbf{Results:} The MCL had a mean origin (humeral) footprint of 216 mm\textsuperscript{2}, insertional footprint of 154 mm\textsuperscript{2}, and surface area of 421 mm\textsuperscript{2}. The LUCL had a mean origin footprint of 136 mm\textsuperscript{2}, an insertional footprint of 142 mm\textsuperscript{2}, and a surface area of 532 mm\textsuperscript{2}. Of the tendons, the triceps maintained the largest insertional footprint, followed by the brachialis and the biceps (\(P < .001-.03\)). The MCL, LUCL, and biceps footprint locations were consistent, with little variability. The surface areas of the anterior (1251 mm\textsuperscript{2}) and posterior (1147 mm\textsuperscript{2}) capsular reflections were similar (\(P = .82\)), and the anterior capsule extended farther proximally.

\textbf{Conclusion:} Restoring the normal anatomy of key elbow capsuloligamentous and tendinous structures is crucial for effective reconstruction after bony or soft tissue trauma. This study provides the upper extremity surgeon with information that may aid in restoring elbow biomechanics and preserving range of motion in these patients.

\textbf{Level of evidence:} Basic Science, Anatomy.

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\textbf{Keywords:} Elbow; anatomy; three-dimensional; ligament; tendon; footprint; surface area

The elbow is an inherently stable joint complex, owing to its bony anatomy and soft tissue reinforcement.\textsuperscript{21} Nevertheless, elbow dislocations occur with an incidence of 5.21/100,000 person-years, often with accompanying avulsion of bone and resulting disruption of tendinous or ligamentous attachments.\textsuperscript{22} Traumatic rupture of the soft
tissue restraints can also occur, most frequently in the overhead-throwing athlete. To restore upper extremity function, reconstruction of the anatomy should proceed with the goal of restoring the normal anatomy of the bony and soft tissues.

The area of attachment of a ligament or tendon to a bony surface, termed the “footprint,” has been identified and described for the rotator cuff.\(^3\)\(^-\)\(^5\) Beginning with Minagawa et al\(^9\) in 1998, the widths of the supraspinatus and infraspinatus tendon footprints were assessed. Folk and Vangness\(^3\) later quantified the supraspinatus tendon length. Dugas et al\(^4\) contributed the first comprehensive evaluation of the rotator cuff footprint, with information on all of the tendinous components collectively, which was later confirmed in a cadaveric study by Curtis et al.\(^4\)

To date, however, the complete analogous anatomy has not been defined for the stabilizing soft tissue structures of the elbow. Farrow et al\(^9\) described the ulnar attachment length, but not the area, of the medial collateral ligament (MCL). Mazzocca et al\(^1\) examined the insertional anatomy of the distal biceps tendon, and Jarrett et al\(^1\) further defined this region into the short and long heads. In addition, Keener et al\(^1\) mapped the insertional footprint of the triceps. Ma and Chang\(^1\) also quantified the brachialis insertion on the coronoid. To the best of our knowledge, however, several periarticular elbow soft tissues, including the lateral ulnar collateral ligament (LUCL) footprints and the surface areas of key capsuloligamentous structures, have not yet been studied. Moreover, previous investigations into the footprint of various tendons and ligaments about the elbow have not considered the structures collectively, and most have used digital or vernier calipers, which provide only coarse and rudimentary measurements.\(^9\)\(^,\)\(^1\)\(^1\)\(^,\)\(^1\)\(^3\)\(^,\)\(^1\)\(^8\)\(^,\)\(^1\)\(^9\)

The purpose of our study was to accurately characterize the major elbow capsuloligamentous and tendinous structure anatomic surface areas and origin and insertional footprints relative to the bony landmarks of the elbow with the use of a precision 3-dimensional mapping system. In doing so, we further sought to compare these measurements among the various soft tissue structures.

Materials and methods

The study evaluated 9 fresh frozen unpaired human cadaveric elbow specimens. Each specimen consisted of an upper extremity extending from the midhumerus to the fingertips. The specimens were from male donors who were a mean age of 69 years (range, 64–72 years). All specimens were stored at \(-4^\circ\)C until evaluation and were thawed to room temperature before dissection. A superficial dissection of skin and subcutaneous tissue from the midhumerus to the midforearm was performed, followed by a deeper dissection to expose the underlying periarticular soft tissue elbow structures. All capsular, ligamentous, and tendinous attachments were preserved and left intact at this point. None of the specimens had evidence of prior injury or surgery to the elbow. To provide a fixed reference point for the digital mapping system, the specimens were rigidly mounted on a custom jig with fixation of the humerus and ulnar shaft with the elbow in 90° of flexion.

The attachments and areas of numerous important ligaments, tendons, and bony landmarks about the elbow, including the MCL, LUCL, triceps, biceps, brachialis, and the anterior and posterior capsular reflections, were characterized using the MicroScribe G2X (Immersion Corp, San Jose, CA, USA) digitizing system and the Optotrak Certus system (Northern Digital Inc, Waterloo, ON, Canada). The MicroScribe G2X has a resolution of 0.23 mm and uses a mechanical tracking system to generate 3-dimensional models of physical objects and structures. Specifically, a pen-like stylus extending from a counter-balanced articulated arm unit was used to outline a region or area of interest (Fig. 1). The Optotrak Certus system functions similarly, with a resolution of 0.1 mm, using a hand-held probe.

Mapping was carefully performed for all major elbow soft tissues and bony prominences. The individual ligaments were dissected out, and the surface area of each was calculated. A large portion of the footprints could be mapped in this position, but for the complete footprint to be characterized, the proximal muscle belly (for tendons) and midportion of the ligaments were sectioned to allow retraction of the soft tissue structure to accurately map the underside of the footprint. With the elbow rigidly fixed proximally and distally, no elbow subluxation was permitted, even after ligamentous sectioning. Each measurement was performed 4 times by the same investigator.

A host computer calculated the position of the stylus in space, and input from the digitizers was analyzed using Rhinoceros 3.0 nonuniform rational basis spline modeling software (McNeel & Assoc, Seattle, WA, USA). A digital image of each elbow specimen was generated, and dimensional features (eg, surface area, length, origin and insertional footprint, and position of footprint relative to bony landmarks) of various structures were calculated from this data. A representative 3-dimensional model is illustrated in Figure 2.

Statistical analyses were performed with SPSS 16.0.1 software (SPSS Inc, Chicago, IL, USA). Mean differences and 95% confidence intervals were calculated, and all comparisons were made with the Mann-Whitney U test. All P values are 2-tailed, with \(P < .05\) indicating significance.
Results

The origin (humeral) and insertional (ulnar or radial) footprints of various elbow periarticular soft tissue structures were analyzed. The results of this assessment are reported in Table I. The MCL had a mean origin footprint of 216 mm$^2$ (standard deviation [SD], 138 mm$^2$) on the humerus and an insertional footprint of 154 mm$^2$ (SD, 79 mm$^2$) on the ulna, whereas the LUCL had a mean origin footprint of 136 mm$^2$ (SD, 67 mm$^2$) and an insertional footprint of 142 mm$^2$ (SD, 90 mm$^2$). The origin and insertional footprints of the MCL were 59% and 8%, respectively, greater than their LUCL footprint counterparts. The difference in origin footprints trended towards significance ($P = .14$), whereas the insertional footprints were statistically similar ($P = .78$).

In addition to characterizing ligamentous attachments, several tendons were also analyzed. Specifically, the mean insertional footprint of the triceps on the olecranon was 646 mm$^2$ (SD, 283 mm$^2$), of the brachialis on the ulna was 371 mm$^2$ (SD, 181 mm$^2$), and of the biceps on the radial aspect of the radial tuberosity was 209 mm$^2$ (SD, 79 mm$^2$). The insertional footprint of the triceps was significantly larger than the footprints of the brachialis ($P = .03$) and the biceps ($P < .001$) tendons, and the footprint of the brachialis was significantly larger than the biceps ($P = .03$). Consequently, the order of tendon insertional footprints, from largest to smallest, was triceps, brachialis, and biceps.

Surface area measurements were also performed to better characterize the capsuloligamentous complex (Table II). The mean surface areas were 421 mm$^2$ (SD, 211 mm$^2$) for the MCL and 532 mm$^2$ (SD, 162 mm$^2$) for the LUCL; thus, the LUCL had 26% more surface area than the MCL. This

| Table I | Footprints of major periarticular elbow soft tissue structures |
|---|---|---|---|---|---|
| Structure | Mean area (mm$^2$) | SD (mm$^2$) | Range (mm$^2$) | 95% CI (mm$^2$) |
| MCL (origin) | 216 | 138 | 44-387 | 126-306 |
| MCL (insertion) | 154 | 79 | 37-257 | 10-205 |
| LUCL (origin) | 136 | 67 | 45-216 | 9-180 |
| LUCL (insertion) | 142 | 90 | 38-310 | 8-200 |
| Triceps (insertion) | 646 | 283 | 263-996 | 46-831 |
| Biceps (insertion) | 209 | 79 | 80-315 | 15-261 |
| Brachialis (insertion) | 371 | 181 | 111-603 | 24-496 |

CI, confidence interval; LUCL, lateral ulnar collateral ligament; MCL, medial collateral ligament; SD, standard deviation.

| Table II | Surface areas of soft tissue structures |
|---|---|---|---|---|
| Structure | Mean surface area (mm$^2$) | SD (mm$^2$) | Range (mm$^2$) | 95% CI (mm$^2$) |
| MCL | 421 | 211 | 291-665 | 182-660 |
| LUCL | 532 | 162 | 351-663 | 348-715 |
| Anterior capsule | 1251 | 351 | 1003-499 | 765-1737 |
| Posterior capsule | 1147 | 432 | 841-452 | 548-1746 |

CI, confidence interval; LUCL, lateral ulnar collateral ligament; MCL, medial collateral ligament; SD, standard deviation.
difference in surface area, however, was not statistically significant ($P = .52$). The anterior capsule had a mean surface area of 1251 mm$^2$ (SD, 351 mm$^2$), whereas the posterior capsule had a surface area of 1147 mm$^2$ (SD, 432 mm$^2$). Although the anterior capsule had a 9% greater surface area, the difference between the anterior and posterior capsules was not significantly different ($P = .82$). Of note, the anterior capsule extended farther proximally, with its most proximal extent lying 25 mm proximal to the transepicondylar axis, whereas the posterior capsule extended 19 mm proximally.

The location of the center of several footprints relative to bony landmarks was also assessed (Fig. 3, Table III). Notably, the origin footprint of the MCL was 19 mm (SD, 3 mm) from the trochlear joint margin, whereas the posterior capsule had a surface area of 1147 mm$^2$ (SD, 432 mm$^2$). Although the anterior capsule had a 9% greater surface area, the difference between the anterior and posterior capsules was not significantly different ($P = .82$). Of note, the anterior capsule extended farther proximally, with its most proximal extent lying 25 mm proximal to the transepicondylar axis, whereas the posterior capsule extended 19 mm proximally.

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distances are measured from the center of the footprint.

### Table III

<table>
<thead>
<tr>
<th>Structure</th>
<th>Mean distance / length (mm)</th>
<th>SD (mm)</th>
<th>Range (mm)</th>
<th>95% CI (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCL origin to trochlear joint margin</td>
<td>19</td>
<td>3</td>
<td>17-23</td>
<td>17-21</td>
</tr>
<tr>
<td>MCL insertion to coronoid margin</td>
<td>10</td>
<td>3</td>
<td>8-15</td>
<td>8-13</td>
</tr>
<tr>
<td>LUCL origin to capitellar margin</td>
<td>10</td>
<td>4</td>
<td>6-15</td>
<td>7-13</td>
</tr>
<tr>
<td>Biceps insertion to radial head margin</td>
<td>34</td>
<td>3</td>
<td>31-38</td>
<td>32-37</td>
</tr>
<tr>
<td>Triceps tendon length</td>
<td>19</td>
<td>1</td>
<td>19-20</td>
<td>19-20</td>
</tr>
<tr>
<td>Olecranon length</td>
<td>33</td>
<td>2</td>
<td>32-34</td>
<td>32-35</td>
</tr>
</tbody>
</table>

CI, confidence interval; LUCL, lateral ulnar collateral ligament; MCL, medial collateral ligament; SD, standard deviation.

The primary objective in treating tendinous and ligamentous elbow injuries is to restore the anatomy and biomechanical function of these structures. To accomplish this, a thorough understanding of the normal anatomy of the major elbow capsuloligamentous and tendinous structures is needed. Although prior investigations have evaluated the insertional footprints of the rotator cuff and their implication on the surgical management of injuries to these tendons, analogous studies of the elbow have been limited.3,4,6,7,13 Our study provides a 3-dimensional anatomic characterization of the major periarticular soft tissue elbow structures. Prior studies were only limited to the evaluation of a single ligament or tendon. Our analysis, however, collectively assessed both primary, such as the MCL and LUCL, and secondary, such as the capsule, static stabilizers of the elbow as well as dynamic stabilizers, including the triceps and brachialis. Furthermore, the extant literature predominantly relied on measurements obtained from vernier or digital calipers, which are unable to accurately measure the area of nongeometric shapes with irregular contours, such as those associated with anatomic footprints. Conversely, our methodology used advanced, precision, computer-assisted mapping technology that can reproducibly and accurately define irregular, 3-dimensional areas of interest.

Characterization of the elbow anatomy included determining the origin (humeral) or insertional (ulnar or radial)
footprints, or both, of several ligaments (MCL, LUCL) and critical tendons (triceps, biceps, and brachialis). The MCL, which is composed of anterior, posterior, and transverse bundles, resists valgus stresses about the elbow.10,17 Its mean origin footprint at the medial epicondyle of the humerus (216 mm²) was 40% larger than its insertional footprint on the ulna (154 mm²). In contrast, Dugas et al7 calculated the mean insertional footprint of the anterior bundle of the MCL (127.8 mm²) was larger than its origin footprint (45.5 mm²). This difference may be attributable to their analysis of a single bundle rather than the entire ligament complex, as performed in our study. Furthermore, the origin and insertional footprints measured in our study were both larger than those found in the Dugas et al study, a finding that further validates our results because one would expect the entire MCL to have larger footprints than any one of its individual bundles. Farrow et al9 also attempted to characterize the entire MCL complex, but only determined a mean length (29.2 mm), rather than area, for the insertional footprint.

In addition to the MCL, the LUCL was also assessed in our study. This ligament, which originates at the lateral epicondyle of the humerus and inserts on the supinator crest of the ulna, endows stability to the radiocapitellar and ulnohumeral articulations and demonstrated some variability in interindividual anatomy.10 Its mean origin footprint (136 mm²) was similar in size to its insertional footprint (142 mm²). Moreover, no significant difference was noted between the MCL and LUCL origin (P = .14) or insertional (P = .78) footprint sizes. Despite its noted importance to elbow stability, to our knowledge, no prior studies have calculated the footprints of the LUCL.8 Accurate measurements of the MCL, especially in the setting of valgus instability with a fractured radial head, and LUCL, notably in the setting of posterolateral rotatory instability, footprints allow for an understanding of partial vs complete ligament tears and are critical to estimate the ideal graft cross-sectional area and bone tunnel size needed to reproduce the normal anatomy with reconstruction.11,15

In addition to ligamentous structures, tendinous insertions were also evaluated. Of these, the triceps maintained the largest insertional footprint, followed by the brachialis and then the biceps (P < .001-.03). Specifically, the triceps had a broad insertion, with a mean footprint of 646 mm², which is in contrast with the 20.9 mm (width) by 13.4 mm (length) footprint described by Keener et al.13 This difference may be due to anatomic variation or the observation that Keener et al13 did not account for the dome-shaped nature of the triceps insertion, which makes the actual area larger (a characteristic for which our study accounted). What instrument the authors used to measure the footprint is also unclear, which could lead to further inaccuracies. The 3-dimensional measuring capabilities of the MicroScribe G2X and Optotrak Certus systems used in our study likely resulted in a more accurate measurement of the actual area. In addition, our analysis revealed that the brachialis insertional footprint was 371 mm². As previously noted, Ma and Chang10 attempted to quantify the brachialis insertional footprint but only calculated a mean length (21.8 mm) rather than an area of attachment. No other prior study has measured the complete footprint area. Furthermore, the biceps had an insertional footprint of 209 mm². This is similar to the findings by Jarrett et al1 who previously evaluated the short and long heads of the distal biceps tendon and concluded that they had a collective insertional footprint of 153 mm².

We noted, however, that the tendon inserted on the radial aspect of the radial tuberosity, whereas prior research demonstrated a more ulnar-sided insertion.18 This discrepancy may stem from specimen and anatomic variation. Ultimately, detailed knowledge of these tendinous footprints is clinically relevant for surgical repair. Many current tendon repair techniques involving suture anchors or bone tunnels may not satisfactorily reproduce the tendinous insertional anatomy.8,13,14

To more fully characterize the soft tissues about the elbow, surface area measurements of the primary capsuloligamentous structures were obtained. Of note, the LUCL had a larger mean surface area (532 mm²) than the MCL (421 mm²); however, this difference was not statistically significant (P = .52). Likewise, the mean surface areas of the anterior (1251 mm²) and posterior (1147 mm²) capsular reflections were similar (P = .82). One previous anatomic cadaveric study quantified the length of distinct anterior and posterior capsular bands; however, to our knowledge, no prior studies have investigated the surface areas of these or other ligamentous elbow structures.21 An understanding of the surface areas will allow for more accurate reconstruction and ensure that appropriate tensile stresses are achieved across these and other graft tissues.24 In addition, precise knowledge of the elbow capsular reflections is clinically useful to avoid intra-articular joint penetration when placing percutaneous or external fixation pins.

Our study also assessed the location of the center of various footprints relative to bony landmarks. Notably, the origin footprint of the MCL was a mean distance of 19 mm from the trochlear joint margin, which is similar to the 19.6-mm distance from the humeral cartilage edge as determined by Dugas et al.7 Moreover, the biceps insertion was a mean of 34 mm from the radial head margin, a slightly longer distance than the 23 mm previously recorded by Athwal et al.2 This discrepancy may be attributable to anatomic variation as well as the observation that Athwal et al2 measured from the most proximal border of the biceps insertion, whereas our study measured from the center (a more distal point and therefore longer distance). Furthermore, our analysis also determined relative positions of the MCL insertion and LUCL origin. Knowledge of the locations of these ligamentous and tendinous origins and insertions is useful to help guide anatomic reconstruction and therefore restore biomechanics and elbow range of motion, especially when injury to these structures makes determining accurate footprint positions challenging.7
This study, however, is not without some limitations. Specifically, our dissections and analysis were limited to 9 cadaveric specimens. Although this exceeds or is similar to the number of cadaveric specimens evaluated in previous studies, future research could be performed on a greater sample size. Also, this study, like prior investigations, was performed only on specimens from adult donors. Consequently, additional research may be needed to characterize the elbow anatomy in pediatric patients. Furthermore, all cadaveric specimens were from male donors, and future studies could be performed on female cadaveric specimens to assess for any potential differences between genders.

Conclusion

Accurate knowledge of the local anatomy of key capsuloligamentous and tendinous structures about the elbow is crucial for effective reconstruction after bony trauma or soft tissue injury. Specific knowledge of the origin and insertion footprints, surface areas, and footprint locations relative to major, recognizable bony landmarks provides the upper extremity surgeon with information to restore both elbow biomechanics and range of motion in these patients. This knowledge can also guide surgical approaches and techniques when soft tissue release is required. Furthermore, the use of 3-dimensional mapping technology enables more reproducible and robust analyses compared with traditional measuring tools. Consequently, these instruments may play an increasingly important role in future musculoskeletal anatomic studies.

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The authors, their immediate families, and any research foundations with which they are affiliated have not received any financial payments or other benefits from any commercial entity related to the subject of this article.

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