SCIENTIFIC ARTICLE

Restoring Isometry in Lateral Ulnar Collateral Ligament Reconstruction

Michael J. Alaia, MD,* Jonathan W. Shearin, MD,† Ian J. Kremenic, MEng,† Malachy P. McHugh, PhD,† Stephen J. Nicholas, MD,† Steven J. Lee, MD†

Purpose To ascertain whether placing the humeral attachment of the lateral ulnar collateral ligament (LUCL) at the humeral center of rotation (hCOR) on the humerus would provide the most isometric reconstruction.

Methods We analyzed 13 cadaver limbs from mid-humerus to the hand. The morphology of the ligament complex was assessed. The hCOR was then found using radiographic parameters. We chose 7 points on the humerus located at and around the hCOR and 3 points paralleling the supinator crest of the ulna and then calculated distances from these points using a digital caliper at 0°, 30°, 60°, 90°, and 130° flexion. Differences in potential ligamentous lengths (termed graft elongation) were then calculated and statistical analysis was performed.

Results There was no perfectly isometric point along the humerus or ulna. However, in all specimens the hCOR was the most isometric point for the humeral reconstruction site, with an average graft elongation of 1.1 mm. Differences in humeral tunnel position dramatically affected graft elongation at all 3 ulnar insertions. Overall, ulnar position had a minimal effect on graft elongation.

Conclusions Although no perfectly isometric points were found, the humeral center of rotation consistently reproduced the most isometry when assessing graft elongation over range of motion. These data may assist surgeons in proper tunnel placement in LUCL reconstruction.

Clinical relevance In LUCL reconstruction, the humeral tunnel should be placed as close as possible to the center of rotation, whereas placement on the ulna is less critical. *(J Hand Surg Am. 2015;40(7):1421−1427. Copyright © 2015 by the American Society for Surgery of the Hand. All rights reserved.)*

Key words Elbow, isometry, lateral ulnar collateral ligament, posterolateral rotatory instability, reconstruction.

Posterolateral rotatory instability (PLRI) of the elbow, described by O'Driscoll and colleagues,[1] causes recurrent pain and instability in patients who have sustained an injury to the elbow, particularly an ulnohumeral dislocation with posterior and valgus displacement. In addition, PLRI can result from multiple corticosteroid injections as well as iatrogenic injury during lateral epicondyle debridement for tennis elbow. Posterolateral rotatory instability includes rotatory subluxation of the radius and ulna away from the humerus without dislocation of the proximal radioulnar joint. The injury classically results from damage to the lateral ulnar collateral ligament (LUCL).

Chronic cases of PLRI have been successfully treated with reconstruction of the LUCL, with acceptable results reported regarding improvements in both pain and stability.[2−6] However, failures of this procedure have been described, possible etiologies of which include failure to comply with the postoperative

*From the *Department of Orthopaedic Surgery, NYU Hospital for Joint Diseases; and the †Department of Orthopaedic Surgery, Lenox Hill Hospital, New York, NY.*

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Corresponding author: Michael J. Alaia, MD, Center for Musculoskeletal Care, 333 East 38th Street, 4th Floor, New York, NY 10016; e-mail: Alaiamj@gmail.com.

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FIGURE 1: The humeral center of rotation was chosen clinically.

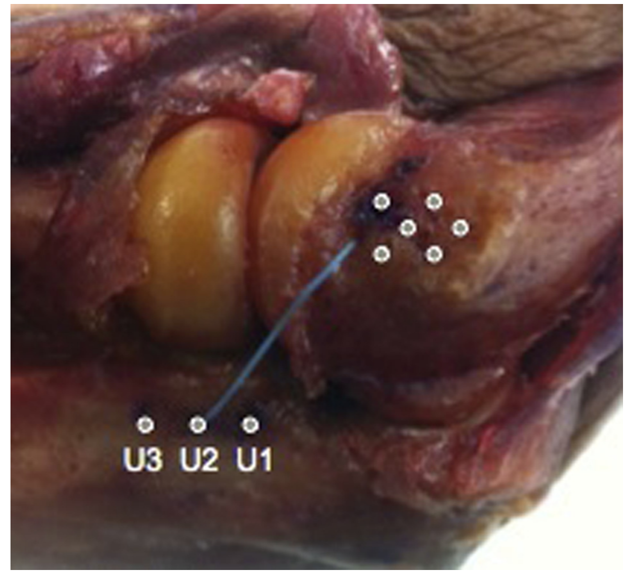

FIGURE 2: The central dot on the humerus represents the center of rotation. The dots directly surrounding the hCOR represent the other positions chosen for our measurements. Not pictured is the 3:45 position, because the border of the epicondylar mound is not represented here. The 3 ulnar dots represent the 3 points chosen on the ulna with respect to radial head landmarks.

protocol, fixation failure, inadequate tensioning of the ligament, and malpositioned bone tunnels leading to anisometric ligamentous reconstruction.

Authors have advocated isometric reconstruction of this ligament. In theory, an isometric reconstruction maintains adequate tension throughout the arc of motion without over-constraining the elbow joint or causing graft stresses. Recent studies have failed to find isometric points, which has led some researchers to question the true isometry of the ligament.[7] In a recent *in vivo* magnetic resonance imaging study, Moritomo and colleagues[7] found the ligament to be anisometric; however, they described the most isometric point on the humerus as being 2 mm proximal to the center of the capitellum. In an anatomic study evaluating humeral and ulnar attachment points, Goren and colleagues[8] failed to find isometric points on the ulna or humerus. However, they described the most isometric points on the ulna as being at locations 16 to 20 mm distal to the proximal aspect of the radial head. The most isometric humeral point was located at the 3:45 position on a clock-face representation of a right lateral epicondyle. The authors did not assess the humeral center of rotation (hCOR) in their study, though, and the morphology of the epicondylar mound may be variable in patients, which limits the strength of the clock-face representation. These reasons may be why the authors found it difficult to locate isometric points.

We hypothesized that the hCOR would be the most isometric point on the humerus with regard to LUCL reconstruction. We also hypothesized that changing the position of the ulnar tunnels would not affect the overall isometry of ligamentous reconstructions.

MATERIALS AND METHODS

For this study, we used 18 cadaver limbs stored at 0°C, thawed, and transected at the mid-humeral level. Specimens with visual evidence of osteoarthritis, documented trauma to the elbow, or surgical procedures performed on the area were excluded. Specimens were also excluded if elbow motion was not full or if there was varus/valgus angulation of more than 20°, which could have indicated prior trauma. Matched pairs of cadavers were excluded to maximize variability among specimens. Five specimens were excluded, which left 13 (mean age, 66 ± 11 y). We removed soft tissue attachments down to the capsuloligamentous layer of the lateral elbow. The capsular attachments and supinator muscle were then excised, leaving only the lateral ligaments. The ligaments were then evaluated and classified according to the method of Cohen and Hastings[9] and

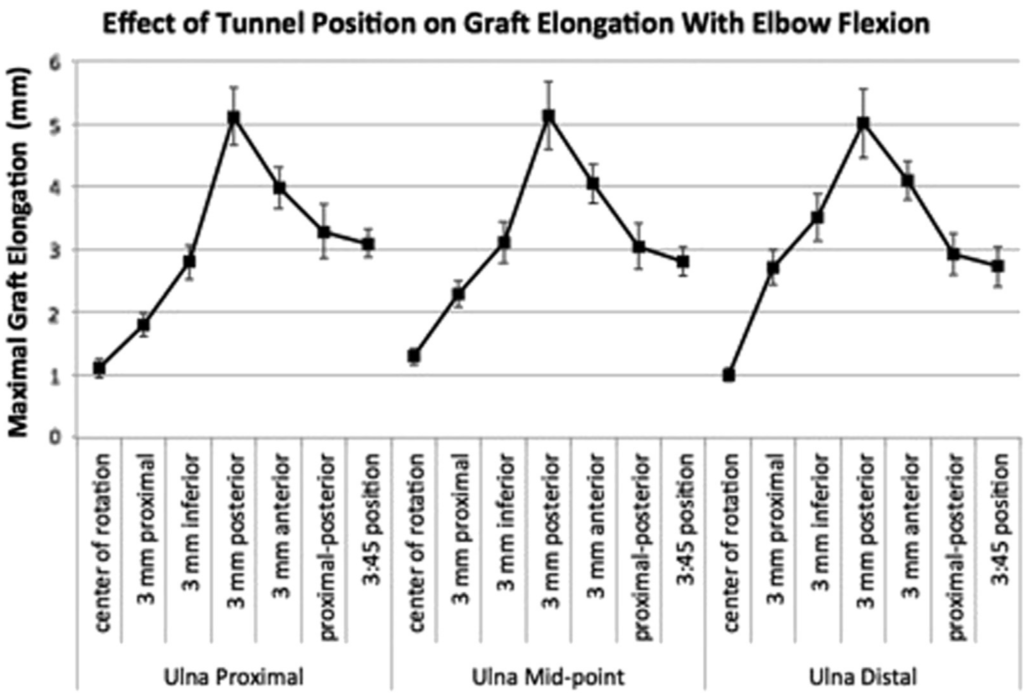

FIGURE 3: Effect of tunnel position on graft elongation with elbow flexion.

TABLE 1. Overall Graft Elongation in Reference to Humeral Position (Averaged Across 3 Ulnar Positions)

	Mean, mm
Center of rotation	1.1 ± 0.47
Proximal	2.3 ± 0.88
Distal	3.1 ± 1.19
Posterior	5.1 ± 1.82
Anterior	4.3 ± 1.12
Proximal/posterior	3.1 ± 1.33
3:45 position	2.9 ± 0.86

modified by Takigawa et al.[10] A type I ligament is bilobed with longitudinal fibers of the LUCL inserting onto the annular ligament and a second bundle inserting distally along the ulna. Type II ligaments are conjoined with the lateral ligaments inserting as a broad single expansion with a smooth transition between the proximal and distal fibers. In type III, the lateral ligaments insert as a broad single expansion along with a thin membranous fiber.

In all specimens, lateral ligaments were intimately associated with the extensor tendon origin off the lateral epicondyle. However, the distal attachment of the ligament was easily isolated in all specimens, and this was used to dissect proximally and develop the plane between the ligamentous complex and the extensor origin. In concordance with other studies,[11] exact separation between the annular ligament, lateral collateral ligament, and LUCL was macroscopically impossible to distinguish proximal to the radial head and remained difficult to distinguish directly superficial to the radial head. Distally, the fibers were more clearly discernible. The morphology of the ligament was diverse: 6 specimens were type I (46%), 3 were type II (23%), and 4 were type III (31%).

Leaving the ligamentous attachments intact, we found the humeral center of rotation found fluoroscopically using a method similar to that described by Bottlang et al.[12] The humerus was rotated until the thick posterior humeral cortical line was approximately 25% to 30% of the distance from the posterior to anterior limits of the humerus. The orientation of the specimen was then modified with respect to abduction and adduction such that concentric circles representing the capitellum and medial condyle were obtained (Fig. 1). We then placed a drill hole using a 1.1-mm Kirschner wire in the center of the concentric circles, marking the hCOR.

The lateral ligaments were then detached, leaving only the distal-most insertional fibers attached to the supinator cristae of the ulna. During the sectioning sequence, we performed pivot shifts to assess for clinical instability after sequential sectioning. The humeral attachment was then completely excised to obtain complete visualization of the capitellum and epicondyle. The proximal-distal length of the radial

TABLE 2. Overall Graft Elongation With Reference to Ulnar and Humeral Positions

Ulnar Position	Humeral Position	Elongation, mm	SD
Proximal	hCOR	1.1	0.15
	Proximal	1.8	0.18
	Distal	2.8	0.28
	Posterior	5.1	0.46
	Anterior	4.0	0.33
	Proximal/posterior	3.3	0.43
	3:45	3.1	0.23
Middle	hCOR	1.3	0.14
	Proximal	2.3	0.21
	Distal	3.1	0.32
	Posterior	5.1	0.55
	Anterior	4.1	0.32
	Proximal/posterior	3.1	0.37
	3:45	2.8	0.23
Distal	hCOR	1.0	0.10
	Proximal	2.7	0.28
	Distal	3.5	0.38
	Posterior	5.0	0.55
	Anterior	4.1	0.31
	Proximal/posterior	2.9	0.33
	3:45	2.7	0.32

head was measured with a digital caliper with a measurement sensitivity of 0.01 mm (Carrera Precision, La Verne, CA), as was the length of the insertional attachment of the LUCL onto the ulna.

We calculated the distance from the hCOR to several points using a right elbow to reference a clock face: the 3:00 (anterior) position of the epicondylar mound and the 4:30 position (the point on the epicondylar mound halfway between the anterior and distal edges of the mound at roughly 45° from the central point of the epicondylar prominence); both were similar to points described by Goren et al.[8] Distances were also measured from the humeral center of rotation to the junctions of the bone and articular cartilage directly anterior, directly distal, and at 45° distal and anterior.

Subsequently, we made 7 drill holes in the humeral epicondyle (Fig. 2) with the 1.1-mm Kirschner wire. Four of these points were at distances 3 mm from the hCOR, located proximally, distally, anteriorly, and posteriorly. Another point was then chosen at the 3:45 position at the junction of the mound of the humeral epicondyle, which was essentially the point on the border of the epicondylar mound halfway between the 3:00 and 4:30 positions, chosen to best represent the point found by Goren et al[8] as the most isometric humeral point. The last point was chosen closer to the prominence of the lateral epicondyle, at a point located 3 mm posterior and 3 mm proximal to the hCOR.

On the ulna, we chose 3 points just posterior to the supinator crest, corresponding to 3 points relative to the radial head. The most proximal point (U1) was at the proximal-most level of the radial head; U3, the distal-most ulnar point, was at the level of the radial head-neck junction. A point located halfway between these points was labeled U2. We then drilled these points with the 1.1-mm Kirschner wire.

Distances from humeral points to each ulnar point for each cadaver were measured at 0°, 30°, 60°, 90°, and 130° elbow flexion to assess for isometry. Reduction of the ulnohumeral joint was maintained throughout the flexion arc. Angles of flexion were confirmed with a goniometer. In total, 105 data points were generated for each limb. After length acquisition, the maximum change in length between different elbow flexion angles was determined for each point on the humerus with each ulnar point, termed graph elongation.

We then compared graft elongation for each series of points with the others to establish the most isometric relationships. We performed statistical analysis using repeated-measures analysis of variance with Bonferroni correction for pairwise comparisons. Statistical significance was set at $P < .050$. Based on previous work, we estimated that with 13 specimens there was 80% power to detect a difference in elongation of 1.5 mm or more between different bone tunnel configurations at $P < .010$ (higher alpha level to account for multiple comparisons).

RESULTS

The mean LUCL distal attachment length on the ulna was 17.2 mm (SD, ±4.1 mm). Type III ligaments had the largest distal ligamentous attachment, with an average of 19.5 mm (SD, ±6.0 mm). The mean distance from the proximal aspect of the radial head to the distal-most attachment point was 18.9 mm (SD, ±5.9 mm). The average longitudinal length of the radial head was 12.2 mm (SD, ±1.6 mm).

Figure 3 represents the overall effect of tunnel position on graft elongation with elbow flexion. In all, changing the attachment position of the humerus caused significant differences in ligament isometry

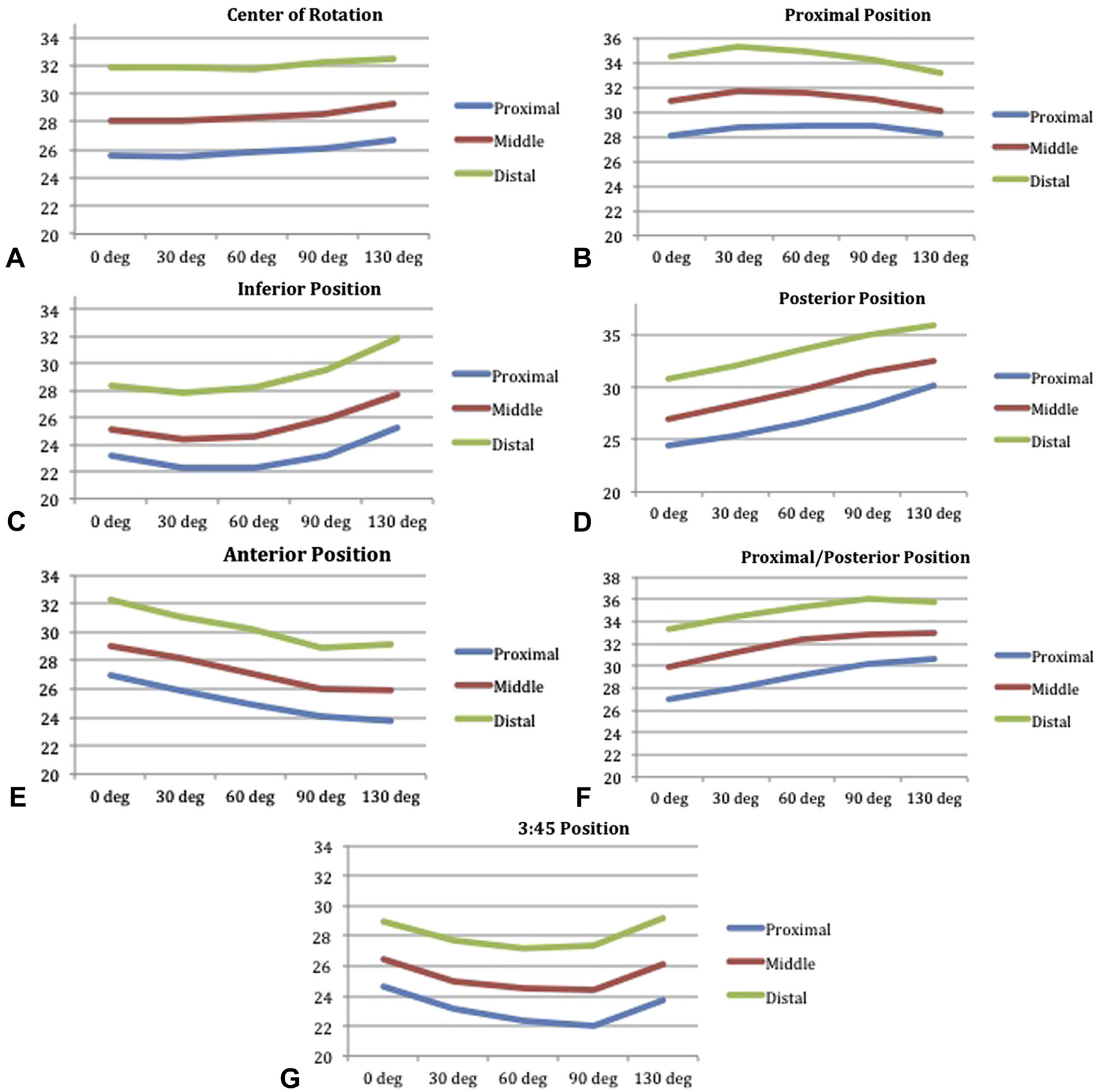

FIGURE 4: Effect of motion on graft length. **A** Center of rotation position. **B** Proximal humeral position. **C** Inferior humeral position. **D** Posterior humeral position. **E** Anterior humeral position. **F** Proximal and posterior humeral position. **G** 3:45 humeral position.

($P < .001$). However, no position induced a perfectly isometric result. The hCOR position proved to be the most isometric in all 13 specimens (Tables 1, 2), with an average graft elongation of 1.1 mm, followed by the 3-mm proximal position (graft elongation, 2.3 mm). The most anisometric humeral position was the 3-mm posterior position, with an average graft elongation of 5.1, followed by the 3-mm anterior position. Figure 4 depicts the trends in length change for each humeral position; for example, the length of the ligament increased through the arc of flexion when the humeral attachment was placed at the 3-mm posterior position and decreased when it was placed in the 3-mm anterior position.

Overall, ulnar position had a minimal effect on graft elongation ($P = .054$); when averaged across humeral positions, there was less than 0.5 mm difference in graft elongation ($P = .220$, .240, and .990 for proximal vs midpoint, proximal vs distal, and midpoint vs distal, respectively). In all, the middle ulnar point was most isometric; however, the overall difference between the most isometric point and least isometric ulnar point was less than 0.1 mm when averages were taken from all points (Table 3).

TABLE 3. Overall Graft Elongation in Reference to Ulnar Position (Averaged Across 7 Humeral Positions)

	Mean, mm
Ulnar proximal	3.2 ± 1.43
Ulnar middle	3.2 ± 1.30
Ulnar distal	3.2 ± 1.30

With regard to the clock-face position on the epicondylar mound, the hCOR was, on average, 2.2 ± 0.9mm (SD, ±0.9 mm) from the 3:00 position and 3.1 ± 1.2 mm (SD, ±1.2 mm) from the 4:30 position. The hCOR was relatively close to the articular cartilage-bone junction: it was 5.5 mm from the anterior junction, 7.5 mm from the distal junction, and 5.8 mm from the distal-anterior junction at a 45° angle.

DISCUSSION

Consistent with the anatomic study performed by Goren et al,[8] we could not find a perfectly isometric point on the humerus. However, we found the hCOR to be the most isometric point on the humerus, with significant increases in anisometry at points away from the hCOR. The consistency of our results proved this to be the case in all 13 cadavers in our series, with overall graft elongation, on average, less than 1.5 mm for the entire arc of motion when the humeral fixation point was located at the center of rotation.

In further agreement with our hypothesis, we found that the ulnar positions chosen did not significantly affect the overall isometry of the reconstruction; there were only small changes in ligamentous length between ulnar positions. Whereas Goren and colleagues[8] found the most isometric point on the humerus to be 16 to 20 mm distal to the proximal aspect of the radial head, we did not find this to be the case. In addition, if the distal-most fibers of the LUCL truly contributed to stability, one could postulate that as the ulnar attachment was placed more distally, improved isometry would have been seen; but this was not the case. The lack of clinical differences with movement of the ulnar tunnels is also supported by biomechanical and kinematic data, which showed that selective release of the distal attachment of the LUCL does not appear to reproduce ulnohumeral subluxation significantly *in vitro*.[13,14]

The importance of this study lies in establishing the foundations for creating the ideal reconstruction for posterolateral elbow stability. Currently, many surgeons use reconstructions that mimic the original description of Jobe et al[15] of ulnar collateral ligament reconstruction. We found that it is difficult to obtain appropriate isometry. Corresponding to our clinical findings, when the humeral tunnel was placed around the 3:45 position, duplicating the technique of Jobe et al for reconstructing the LUCL, it produced a mean 3.1 mm of graft elongation. We believe that a simple, isometric, one-stranded graft fixed into one point on the ulna and closely approximating the center of rotation on the humerus can simplify the procedure while closely restoring isometry and achieving appropriate stability.

Theoretically, an ideal reconstruction would emulate the position of the native LUCL. However, in accordance with prior studies, we found wide variation in the morphology of the lateral ligaments. In our sectioning, we also found a variably large surface area of the osseous attachments, with some fibers of the lateral ligaments attaching extremely close to the articular cartilage of the capitellum. Therefore, a true anatomic reconstruction would not only be difficult to reproduce but might put the articular junction of the capitellum at considerable risk.

A more realistic reconstruction would allow a tendon or ligament graft to be safely and easily placed in a position as isometric as possible to provide posterolateral stability throughout a full range of motion. Based on this study, proximally, the graft should be placed as close as possible to the humeral center of rotation. The type of fixation used may slightly alter the positions of drill holes such that the affixed graft can be as close to the center of rotation as possible. On the ulna, placement of graft is less crucial as long as it is placed along the supinator crest. We are now using one ulnar drill hole placed in line with the mid-portion of the radial head (position U2). If 2 ulna drill holes are preferred, we recommend positions U1 and U3 so that stability can be maintained without compromising the integrity of the bony bridge.

There are several limitations to this study. First, the limbs were held reduced by the surgeons and distances were obtained manually using a digital caliper. In addition, the center of rotation in all specimens was estimated using fluoroscopy and 2-surgeon agreement instead of advanced imaging or motion analysis. This could predispose the results to human error; however, we believe that the consistency in our results with little variation was a sign of accuracy and reproducibility. Also, no force studies were performed. Therefore, although we were able to demonstrate significant differences in isometry, it is still unclear whether these results will be clinically relevant when reconstructions are performed, which is a potential site for further study. In addition, we did not quantify the true dimensions of the ligament attachments onto the humerus because of the difficulty of obtaining precise separation from the lateral extensor tendons, which would have introduced error into our measurements.

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