Biomechanical Comparison of Anatomic Restoration of the Ulnar Footprint vs Traditional Ulnar Tunnels in Ulnar Collateral Ligament Reconstruction

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Background: Current techniques for ulnar collateral ligament (UCL) reconstruction do not reproduce the anatomic ulnar footprint of the UCL. The purpose of this study was to describe a novel UCL reconstruction technique that utilizes proximal-to-distal ulnar bone tunnels to better re-create the anatomy of the UCL and to compare the biomechanical profile at time zero among this technique, the native UCL, and the traditional docking technique.

Hypothesis: The biomechanical profile of the anatomic technique is similar to the native UCL and traditional docking technique.

Study Design: Controlled laboratory study.

Methods: Ten matched cadaveric elbows were potted with the forearm in neutral rotation. The palmaris longus tendon graft was harvested, and bones were sectioned 14 cm proximal and distal to the elbow joint. Specimen testing included (1) native UCL testing performed at 90° of flexion with 0.5 N·m of valgus moment preload, (2) cyclic loading from 0.5 to 5 N·m of valgus moment for 1000 cycles at 1 Hz, and (3) load to failure at 0.2 mm/s. Elbows then underwent UCL reconstruction with 1 elbow of each pair receiving the classic docking technique using either anatomic (proximal to distal) or traditional (anterior to posterior) tunnel locations. Specimen testing was then repeated as described.

Results: There were no differences in maximum load at failure between the anatomic and traditional tunnel location techniques (mean ± SD, 34.90 ± 10.65 vs 37.28 ± 14.26 N·m; P = .644) or when including the native UCL (45.83 ± 17.03 N·m; P = .099). Additionally, there were no differences in valgus angle after 1000 cycles across the anatomic technique (4.58° ± 1.47°), traditional technique (4.08° ± 1.28°), and native UCL (4.07° ± 1.99°). The anatomic group and the native UCL had similar valgus angles at failure (24.13° ± 5.86° vs 20.13° ± 5.70°; P = .083), while the traditional group had a higher valgus angle at failure when compared with the native UCL (24.88° ± 6.18° vs 19.44° ± 5.86°; P = .015).

Conclusion: In this cadaveric model, UCL reconstruction with the docking technique utilizing proximal-to-distal ulnar tunnels better restored the ulnar footprint while providing valgus stability comparable with reconstruction with the docking technique using traditional anterior-to-posterior ulnar tunnel locations. These results suggest that utilization of the anatomic tunnel location in UCL reconstruction has similar biomechanical properties to the traditional method at the time of initial fixation (ie, not accounting for healing after reconstruction in vivo) while keeping the ulnar tunnels farther from the ulnar nerve. Further studies are warranted to determine if an anatomically based UCL reconstruction results in differing outcomes than traditional reconstruction techniques.

Clinical Relevance: Current UCL reconstruction techniques do not accurately re-create the ulnar UCL footprint. The UCL is a dynamic constraint to valgus loads at the elbow, and a more anatomic reconstruction may afford more natural joint kinematics. This more anatomic technique performs similarly to the traditional docking technique at time zero, and the results of this study may offer a starting point for future in vivo studies.

Keywords: elbow; ulnar collateral ligament; baseball; biomechanics; cyclic loading; pediatrics

Ulnar collateral ligament (UCL) injuries of the elbow were first described in a javelin thrower in 1946.[26] Since then, the injury has most often been described in baseball players. Over the past few decades, UCL injuries have been seen in increasing frequency. Hodgins et al[14] found an increased

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rate of UCL reconstruction in New York State, most notably in patients between 15 and 20 years old. Fleisig and Andrews[13] noted a 22-fold increase in the incidence of UCL reconstruction at their institution from 1994 to 2010. They cited increased sports participation and awareness of the injury as potential factors contributing to the rise in cases.

The first UCL reconstruction of the elbow was performed by Dr Frank Jobe in 1974. In his classic technique, first described in 1986, a palmaris longus tendon autograft was shuttled through tunnels in the ulna and humerus in a figure-of-8 fashion.[15] To access the UCL and the ulnohumeral joint, the flexor pronator mass (FPM) was detached from the medial epicondyle, and a submuscular ulnar nerve transposition was performed. The ulnar tunnel was created by drilling 2 holes anterior and posterior to the sublime tubercle. A single humeral tunnel was made at the medial epicondyle, with 2 converging tunnels created from the cubital tunnel. The graft was then placed in a figure-of-8 fashion and sewn to itself. Because of the morbidity associated with FPM detachment and a high rate of ulnar nerve complications accompanying the submuscular ulnar nerve transposition in the classic Jobe technique, approaches were developed to preserve the FPM and anteriorly directed humeral tunnels.[2,16,24,25] Remaining concerns over the technical demands of humeral tunnel creation, graft fixation, and graft passage led to the development of the docking technique.[23] Now widely adopted as an alternative to the modified Jobe technique, the docking technique has demonstrated similar outcomes to the modified Jobe technique when the FPM is preserved and no ulnar nerve transposition is performed.[16]

More recently, there have been anatomic studies showing the distal ulnar insertion to be more elongated than previously thought.[8,11,12] Farrow et al[12] measured the mean length of the distal ulnar footprint to be 29.2 mm and demonstrated on all specimens an osseous ridge that extended distally from the sublime tubercle. Camp et al[8] revealed similar findings, with an average insertional footprint of 29.7 mm and an average total area of 187.6 mm^2. Similarly, Dutton et al[11] measured a mean insertional footprint of 27.4 mm and total anterior bundle footprint area of 216.9 mm^2. These findings have some authors questioning whether the current ulnar tunnels, created anterior and posterior to the sublime tubercle, are sufficient in re-creating the ulnar footprint.

Therefore, we propose a more anatomic technique to incorporate the restoration of the ulnar footprint in UCL reconstruction. The purpose of this study was to describe a proximal-to-distal ulnar tunnel technique to restore the anatomic footprint during UCL reconstruction and to evaluate its biomechanical properties. We hypothesized that there would be no significant differences in valgus angle at failure and load at failure between docking using the anatomic and traditional ulnar tunnel locations.

METHODS

Specimens

Ten matched pairs of fresh-frozen cadaveric elbows (n = 20; 7 male, 3 female; mean ± SD age, 56.5 ± 6.7 years) were procured and stored at –20°C. Specimens were thawed 12 hours before being dissected free of all soft tissue, except for the capsule and the medial and lateral ligament complexes. The palmaris longus tendon was harvested. If the palmaris longus tendon was not present, the flexor digitorum superficialis tendon was harvested instead. Tendon grafts were wrapped in normal saline solution–soaked gauze and stored at –20°C. The bones were transected 14 cm proximal and distal to the elbow joint. Both bone ends were potted in polyvinyl chloride pipes (length, 6.35 cm; diameter, 3.81 cm) with fiberglass resin (Bondo; 3M Company) in neutral forearm rotation. Specimens were thawed overnight before testing. Testing was conducted at room temperature, and saline solution–soaked gauze was used to keep all capsule and ligament complex tissues moist throughout testing. All study procedures were reviewed and approved by the institutional review board of Walter Reed National Military Medical Center.

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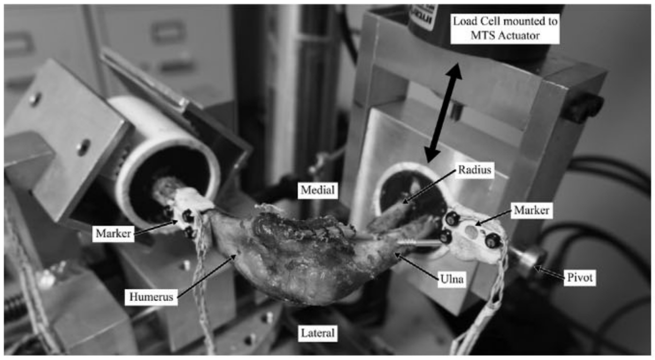

Figure 1. Left elbow specimen in 90° of flexion with the potted radius and ulna (right) mounted to the servohydraulic materials testing system (MTS) and with the potted humerus (left) positioned parallel to the floor and rigidly mounted by a clamp. The ulnar collateral ligament was reconstructed using the anatomic tunnel location, and the potted radius and ulna were subjected to cyclic valgus loading and load to failure by the actuator (not shown). The setup attached to the load cell allowed for rotation (at the pivot point) and pistoning to maintain a constant moment arm length. Infrared markers were attached to the humerus and ulna to record the 3-dimensional kinematics.

Biomechanical Testing

The forearm was mounted on a servohydraulic materials testing system (MTS 858 Mini Bionix II; MTS Systems Corp), and the humerus was positioned parallel to the floor with the elbow in 90° of flexion (Figure 1). The moment arm was determined as the distance from the center of the elbow joint to the axis of the actuator using a ruler. Native UCL testing was performed at 90° of flexion, preloaded at 0.5 N·m of valgus moment for 15 seconds, cyclically loaded from 0.5 to 5 N·m (4- to 40-N axial load, 12.5 cm from the elbow joint) for 1000 cycles at 1 Hz, and then loaded to failure at a constant axial traction rate of 0.2 mm/s. Failure occurred when the joint failed to maintain 25% of the maximum moment detected or when the valgus angle exceeded 30° during traction. Force and displacement were continuously measured at a 102-Hz sampling frequency. Infrared rigid body markers (Optotrak Certus; Northern Digital, Inc) were attached to the humerus and ulna to record the 3-dimensional kinematics of the bones. Valgus moment and angle were calculated from the actuator force, actuator displacement, and moment arm. After failure, specimens were inspected for mode of failure and graft integrity.

Experimental Design

After the biomechanical testing of the native UCL, matched pairs were randomly assigned to and underwent UCL reconstruction with the docking technique using 1 of 2 tunnel locations: traditional (anterior to posterior) (Figure 2B) or anatomic (proximal to distal) (Figure 2A). Preparation of the palmaris graft and medial humeral epicondyle docking socket was identical for both techniques and was performed in a manner consistent with previous studies.[4]

Traditional Docking Technique. The docking technique was performed as previously described by Rohrbough et al.[23] (Figure 2B). Briefly, two 3.5-mm holes were drilled anterior and posterior to the sublime tubercle. The tunnels were then connected with a curved curette. On the humerus, a socket of 15 mm in length was drilled along the medial epicondylar axis, with an aperture at the native UCL anterior bundle anatomic attachment on the anterior inferior aspect of the medial epicondyle using a 4.0-mm bit. Two small exit holes were created at the proximal end of the socket anteriorly with a 1.5-mm drill bit, separated by a bone bridge of 5 to 10 mm.

One limb of the palmaris graft was whipstitched with a No. 2 nonabsorbable suture (FiberWire; Arthrex Inc), and this end was passed through the ulnar tunnel and docked into the humeral tunnel with the suture ends exiting one of the two 1.5-mm holes. With the elbow reduced

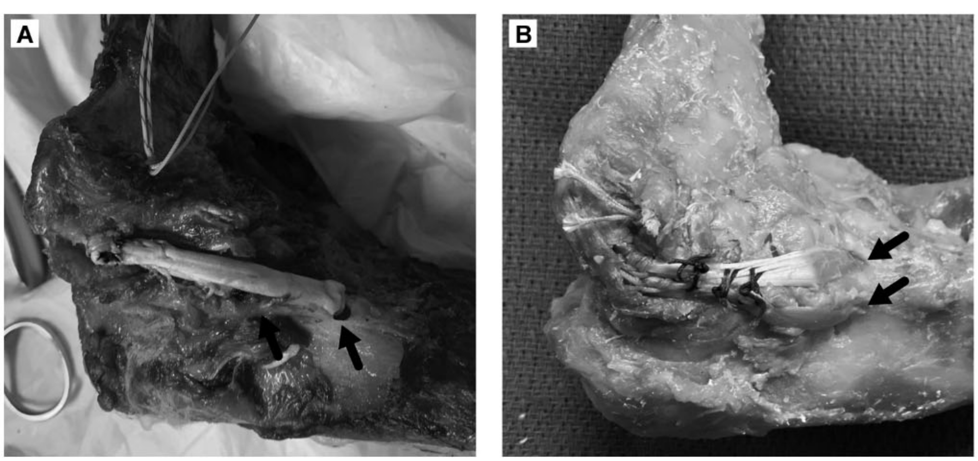

Figure 2. (A) Left elbow specimen reconstructed with the docking technique using the anatomic tunnel location (proximal-to-distal ulnar tunnels; black arrows). (B) Left elbow specimen reconstructed with the docking technique using the traditional tunnel location (anterior-to-posterior ulnar tunnels; black arrows).

and the forearm in maximum supination, graft tension was maintained while a gentle varus stress was applied, and the elbow was ranged from flexion to extension repeatedly to reduce graft creep. Graft length was then determined by holding the free limb of the graft adjacent to the humeral tunnel with the elbow in roughly 30° of flexion and estimating the length needed to achieve appropriate graft tension without bottoming out in the tunnel. The free limb was marked and prepared with another No. 2 nonabsorbable suture, and excess tendon was removed. This limb was then docked in the humeral tunnel, and with the forearm maximally supinated and a gentle varus stress applied, the sutures were tied over the humeral bone bridge with the elbow in roughly 30° of flexion.

Anatomic Footprint Technique. For the anatomic footprint specimen, two 3.5-mm drill holes were placed to create a tunnel along the medial ulnar ridge proximally and distally in line with the anatomic footprint of the UCL (Figure 3A). The drill holes were spaced approximately 2 cm apart with the proximal hole starting just at the level of the sublime tubercle. The proximal hole was made with the drill angled distally to provide a smooth passage of the graft into the ulna. The distal ulnar tunnel was drilled at a right angle to the bone to minimize a sharp edge that could injure the graft as it exited and turned back proximally. A small curved curette was used to connect the tunnels to ensure smooth passage of the graft. A countersink was used to chamfer the proximal edges of each drill hole to minimize abrasion on the graft. This was especially critical at the distal ulnar tunnel where the graft exited and made a 180° turn back proximally. The humeral tunnels were created in the same manner as the docking technique.

One limb of the palmaris graft was whipstitched with a No. 2 nonabsorbable suture. The graft was then passed through the ulnar tunnel from proximal to distal, and this end was passed through the ulnar tunnel and docked into the humeral tunnel with the suture ends exiting one of the two 1.5-mm holes (Figure 3, B and C).

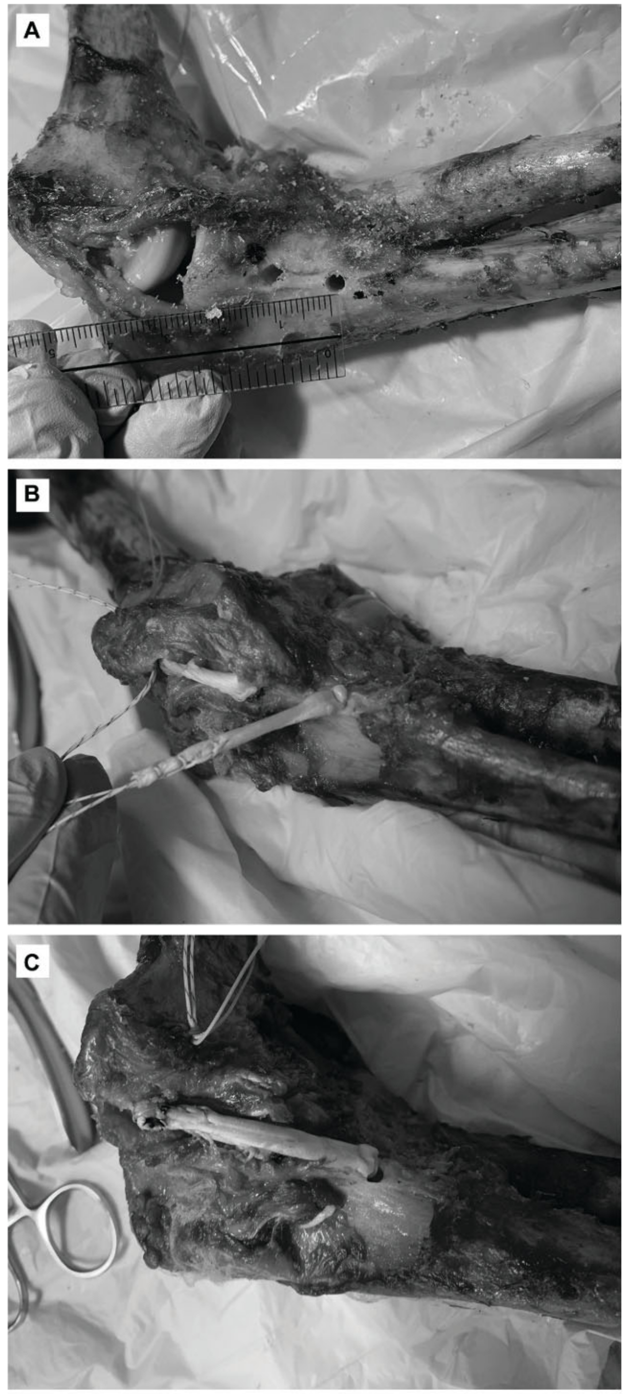

Figure 3. (A) Sequential photographs of a left elbow undergoing anatomic ulnar collateral ligament reconstruction. Anatomic tunnel locations are depicted with a ruler for reference. (B) One limb of the palmaris longus graft is docked into the humeral tunnel. The second limb is referenced at the exit hole of the humeral tunnel, and the excess graft is excised. The remaining limb is then whipstitched. (C) Final photograph demonstrates a completed reconstruction.

Data Reduction

Force and displacement data were filtered using a fourth-order zero-lag Butterworth filter (f_{sampling} = 102 Hz, f_{cutoff} = 1 Hz) and converted to moments and valgus angles, respectively, with custom MATLAB scripts (R2020a; MathWorks Inc). Valgus angle was analyzed at discrete cycles (1, 10, 100, and 1000 cycles). Maximum moment at failure and mode of failure were recorded. Modes of failure included suture pull-through, suture rupture, and bone fracture. Descriptive statistics were calculated for maximum moment at failure, valgus angle at discrete cycles, and maximum valgus angle at failure.

Statistical Analysis

An a priori power analysis was conducted for a paired *t* test using data from similar previously published studies to determine the minimum required sample size.[4,10,17,19] A 10 N·m SD was determined per the average standard deviation from prior studies. To detect a 10-N·m difference in maximum valgus moment at failure between the tunnel techniques (anatomic vs traditional), a sample size of 10 matched pairs was determined to provide 80% power at

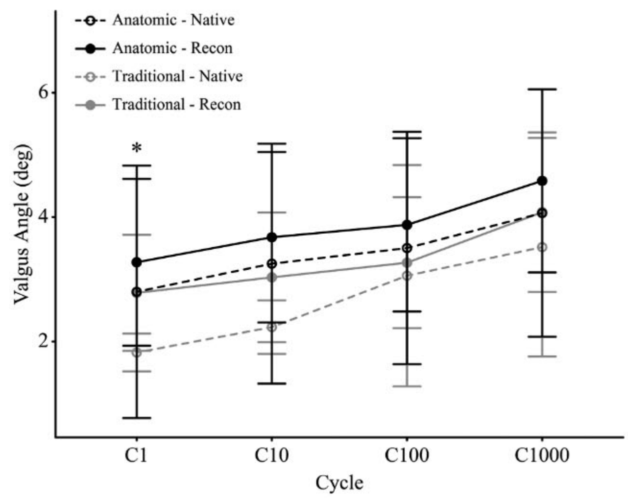

Figure 4. Elbow valgus angle (mean ± SD) at cycles 1, 10, 100, and 1000 for the native ulnar collateral ligament and reconstructed anatomic and traditional tunnel location groups. Asterisk (*) indicates significantly greater valgus angle in the reconstructed specimens vs native specimens within the traditional tunnel location group at cycle 1 (P = .049).

α = .05. Paired t tests compared mean maximum moments at failure and mean maximum valgus angles at failure between the traditional and anatomic tunnel location groups. Two-way repeated measures analysis of variance analyzed valgus angle at the prescribed discrete cycles. Normality assumption was assessed by the Shapiro-Wilk test. The Levene test inspected the homogeneity of variance in the data. Post hoc pairwise t tests adjusted using the Bonferroni correction method were used in the event of significant differences between groups. The significance level was set a priori at α = .05. All statistical analyses were performed using R (4.0.2) in RStudio (Version 1.3; RStudio, Inc) using the rstatix package.

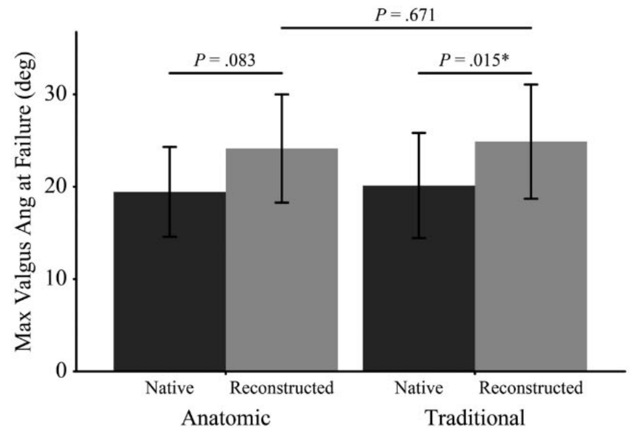

Figure 5. Maximum elbow valgus angle (mean ± SD) at failure for native and reconstructed anatomic and traditional location groups.
*Statistically significant at the 95% confidence level.

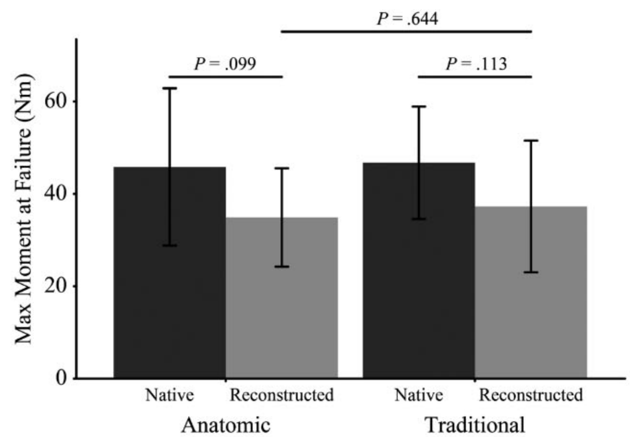

Figure 6. Maximum valgus moment (mean ± SD) at failure for native and reconstructed anatomic and traditional tunnel location groups.

RESULTS

For all cycles, there were no differences in valgus angle between the anatomic (proximal to distal) and traditional (anterior to posterior) tunnel location groups (Figure 4). Within the anatomic tunnel location group, valgus angles were similar between reconstructed and native specimens for all cycles. Within the traditional tunnel location group, valgus angle was greater in reconstructed specimens as compared with native specimens at cycle 1 but were similar at the following cycling intervals. Additionally, there were no differences in valgus angle after 1000 cycles across the anatomic technique (4.58° ± 1.47°), traditional technique (4.08° ± 1.28°), and native UCL (4.07° ± 1.99°) (P = 0.403 and P = 0.188 respectively).

Maximum valgus angle at failure did not differ between UCL reconstruction using the anatomic and traditional tunnel locations (24.13° ± 5.86° vs 24.88° ± 6.18°, P = 0.671; Figure 5). However, maximum valgus angle at failure was greater in reconstructed elbows as compared with native elbows within the traditional tunnel location group (24.88° ± 6.18° vs 19.44° ± 5.86°; P = 0.015) whereas there was no significant difference between native and reconstructed elbows in the anatomic tunnel location group (24.13° ± 5.86° vs 20.13° ± 5.70°; P = .083). There was no difference in maximum moment at failure between UCL reconstruction using the anatomic and traditional tunnel locations (34.90 ± 10.65 vs 37.28 ± 14.26 N m; P = .644; Figure 6). Additionally, there was no significant difference in the maximum moment at failure between the anatomic or traditional reconstruction and the native UCL (34.90 ± 10.65 vs 45.83 ± 17.03 N m, P = .099 and 37.28 ± 14.26 vs 46.75 ± 12.17 N m, P = .113 respectively; Figure 6).

Suture pull-through at the graft end docked in the humeral tunnel was the predominant mode of failure (anatomic tunnel group, n = 8; traditional tunnel group, n = 9; 85% overall). Two specimens reconstructed using the anatomic tunnel locations failed via suture rupture at the humeral tunnel drill hole. One specimen reconstructed using the traditional tunnel location failed via fracture at the ulnar tunnel. There were 2 specimens that required a flexor digitorum superficialis tendon graft in the anatomic group and 1 in the traditional group, and all these specimens failed by suture pull-through at the humeral docking site. No specimens demonstrated evidence of graft tear or attritional wear at the ulnar tunnel sites.

DISCUSSION

The traditional UCL reconstruction (docking and modified Jobe techniques) centers the ulnar tunnels anterior to posterior over the sublime tubercle, whereas the anatomic technique places these tunnels proximal to distal to better re-create the native UCL footprint. In our study, we found no significant differences in maximum valgus angle at failure or load to failure between the traditional docking technique and the anatomic technique. Additionally, there was no significant difference in valgus angle between the techniques after cyclic loading. There was also no significant difference between either technique and the native UCL regarding load at failure; however, the traditional docking technique showed an increased valgus angle at failure as compared with the native UCL, whereas the anatomic technique, while very close to demonstrating increased valgus angle, did not (P = .083).

The docking technique has been widely accepted as an alternative to the modified Jobe technique and has been the subject of several biomechanical investigations.[3,4,9,11,17-20,22] Because the docking technique is one of the most commonly used methods for UCL reconstruction[6,9,16] and an alternative developed to address the technical demands of the figure-of-8 technique (eg, exact placement and connection of the "Y" pattern drill tunnels and steep learning curves with regard to graft passage and tensioning),[7] we thought that comparison of the ulnar tunnel locations with the docking technique would contribute to the literature. Additionally, we subjected native specimens to the same testing parameters as reconstructed specimens to directly examine the performance of each technique relative to the native UCL. Ultimately, there were no differences between techniques, but the traditional docking technique had a higher valgus angle at failure as compared with native specimens. A potential explanation for this finding is that a more proximal tunnel location with a smaller footprint along the ulna affords a longer lever arm and results in a greater valgus angle at maximal load. Although this is a possibility, there was no significant difference in valgus angle at failure between reconstruction groups. Additionally, Dutton et al[11] found no difference in valgus angle or load at failure in a comparison of the traditional docking technique and ulnar tunnel location along the anatomic footprint.

Anatomically based ulnar tunnels for UCL reconstruction offer some advantages over the traditional docking technique. The UCL has a long triangular insertion on the ulna, and tunnels placed along the axis of the ulna create a graft that is more isometric to the native UCL. Additionally, the linear orientation of the graft along the ulna results in a greater surface area for tendon-bone healing, which may result in a stronger construct in vivo. Furthermore, the traditional posterior ulnar tunnel may place the ulnar nerve at risk, whereas the tunnels in this anatomic technique are more remote from the ulnar nerve and may theoretically decrease the risk of iatrogenic injury. In addition, our technique may allow for easier visualization of the graft on ultrasound and magnetic resonance imaging as the 2 limbs are stacked onto each other. Finally, the anatomic position of the new graft in our technique may allow for easier suturing of the graft to the remnant native ligament, as is commonly performed.

In a recent biomechanical study, Camp et al[5] compared the docking technique with a novel technique designed to re-create the ulnar UCL footprint. In this onlay technique, the ulnar side of the graft is anchored proximally with 2 suture anchors near the joint line, and the distal limbs of the graft are secured with a suture button at the distal aspect of the UCL footprint. The humeral side of the graft is secured similarly to the docking technique. The authors found greater load at failure using the onlay anatomic technique as compared with the docking technique (31.9 ± 8.4 vs 23.8 ± 6.1 N·m). Conversely, we saw no difference in mean load at failure between our anatomic bone tunnel technique and the docking technique (34.9 ± 10.7 vs 37.3 ± 14.3 N·m). The anatomic techniques have similar loads at failure that approximate previously reported native UCL strengths (22-34 N·m),[1,4,5,19] and we found no difference between the anatomic technique and native UCLs in this study. Additionally, while the onlay anatomic technique relies on surface healing along the ulna, the anatomic bone tunnel technique affords surface and intracortical graft-to-bone healing without additional implants. One concern of the anatomic bone tunnel technique is the sharp turn of the graft required by the proximal-distal tunnel position. We addressed this concern by chamfering the edges of the ulnar bone tunnels, and we saw no evidence of graft tear or attritional wear after testing. Both techniques compare favorably with the traditional docking techniques based on previously published loads at failure,[4,9,17] and both techniques appear to represent viable options for an anatomically based UCL reconstruction.

This study has several limitations. As a cadaveric biomechanical study, these results reflect the performance of each technique at time zero and do not account for the effects of tendon-bone healing over time. Although there was no difference between reconstruction groups at time zero, in vivo clinical studies are needed to investigate whether these results apply clinically. Additionally, the mean age of these specimens was 56.5 years. Even though this is older than the typical age for patients receiving UCL reconstruction, this specimen age is consistent with similar UCL reconstruction studies.[4,5,20,27] Another potential limitation is that not all specimens were able to be tested with a palmaris longus tendon graft; however, the 2 specimens in the anatomic group and the 1 specimen in the traditional group that used an flexor digitorum superficialis tendon graft demonstrated testing outcomes similar to the means of their respective groups. Furthermore, we tested elbows in 90° of flexion and in neutral forearm rotation, which affords a degree of bony stabilization to the elbow. Additionally, Ciccotti et al[9] evaluated elbow stability under valgus stress and found increased stability at higher flexion angles. Although the anterior band of the

UCL is not isolated at 90°, this is the general elbow position in the late cocking and early acceleration phase of throwing, when the UCL sees the highest force.[4] Previous studies have examined UCL reconstruction at various flexion angles in efforts to isolate the anterior bundle, testing the elbow between 30° and 40° of flexion in full supination or dynamically between 30° and 120°, where it provides the most significant restraint to valgus stress; yet, there is no recognized standard for testing the UCL under cyclic load.[1,4,10,17,18,21,22] Despite these limitations, the methodology of this study is consistent with previous biomechanical models and generally representative of valgus stress at the elbow during throwing.

CONCLUSION

UCL reconstruction with the docking technique utilizing proximal-to-distal ulnar tunnels better restored the ulnar footprint while providing valgus stability comparable with reconstruction with a docking technique using traditional anterior-to-posterior ulnar tunnel locations in this cadaveric model. These results suggest that utilization of the anatomic tunnel location in UCL reconstruction has similar biomechanical properties as compared with the traditional method at the time of initial fixation (ie, not accounting for healing after reconstruction in vivo) while keeping the ulnar tunnels farther from the ulnar nerve. Further studies are warranted to determine if an anatomically based UCL reconstruction results in differing outcomes as compared with traditional reconstruction techniques.

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