Biomechanical Comparison of Ulnar Collateral Ligament Reconstruction Between Palmaris Longus Autograft and Knee Medial Collateral Ligament Allograft

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Background: Medial ulnar collateral ligament (mUCL) injury can cause significant pain and alter throwing mechanics. Common autograft options for mUCL reconstruction (UCLR) include the palmaris longus (PL) and hamstring tendons. Allograft use may reduce donor site morbidity and decrease function related to PL autografts.

Purpose: To compare varus stability and load to failure between a novel allograft for UCLR—knee medial collateral ligament (kMCL)—and a PL autograft in human donor elbow specimens.

Study Design: Controlled laboratory study.

Methods: A total of 24 fresh-frozen human elbows were dissected to expose the mUCL. Medial elbow stability was tested with the mUCL intact (native), deficient, and reconstructed utilizing the humeral single-docking technique with either a (1) kMCL allograft (n = 12) or (2) a PL autograft (n = 12). A 3-N·m valgus torque was applied to the elbow, and valgus rotation of the ulna was recorded via motion tracking cameras. The elbow was cycled through a full range of motion 5 times. After kinematic testing, specimens were loaded to failure at 70° of elbow flexion, and failure modes were recorded.

Results: The mUCL-deficient elbows demonstrated significantly greater valgus rotation compared with the intact and reconstructed elbows at every flexion angle tested (10°-120°) (P <.001). Both kMCL- and PL-reconstructed elbows exhibited significantly higher mean valgus rotation compared with the intact state between 10° and 40° of flexion ($P < .01$). There were no significant differences in valgus rotation at any flexion angle between the kMCL and PL graft groups. When loaded to failure, elbows reconstructed with both kMCL and PL grafts failed at similar torque values (18.6 ± 4 and 18.1 ± 3.4 N·m, respectively; P = .765).

Conclusion: Fresh-frozen and aseptically processed kMCL allografts demonstrated similar kinematic and failure properties to PL tendon autografts in UCL-reconstructed elbows, although neither graft fully restored kinematics between 10° and 40°.

Clinical Relevance: Prepared kMCL ligament allografts may provide a viable graft material when reconstructing elbow ligaments while avoiding the potential complications related to PL autografts— including donor site morbidity.

Keywords: allograft; knee medial collateral ligament; palmaris longus; semitendinosus; Tommy-John; ulnar collateral ligament reconstruction; biomechanical

Injury to the medial ulnar collateral ligament (mUCL) of the elbow can be devastating for throwing athletes. This injury commonly occurs in baseball pitchers as a result of valgus overload in the late-cocking phase of the throwing cycle.[2] Common symptoms reported include medial-sided

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elbow pain at the flexor-pronator origin and instability with valgus-directed stress from 30° to 100° of flexion, depending on which bundles of the mUCL have been compromised.[2] For patients with acute complete ligament tears or avulsions, mUCL reconstruction (mUCLR) can be considered. The prevalence of professional baseball players having undergone UCL reconstruction (UCLR) has increased[17] to 13%. The original technique for UCLR, described by Dr. Frank Jobe, involved detaching the flexor-pronator mass from the medial epicondyle.[12] Of the subsequent modifications to this technique, no single technique has proven to be superior.[25] Outcomes have been favorable, with a return to sports rate as high as 86% reported in the literature.[7]

An important consideration of UCLR is graft selection. Common grafts employed by orthopaedic surgeons include either palmaris longus (PL) or hamstring tendon autografts. The PL autograft is typically harvested through 2 small transverse incisions made at the wrist crease and about 4 cm proximally.[2] After the palmaris tendon is isolated from the medial nerve and other flexor tendons, a third incision about 15 cm proximally is used to identify the proximal end of the palmaris tendon.[2] Considered the gold standard graft source, the PL was initially thought to contribute minimally to upper extremity function, and thus has naturally become the most frequently used graft in UCLR.[2,11] However, this perception may not be completely accurate, as a recent study demonstrated that the PL tendon may contribute to upper-extremity torque generation in athletes.[5] Thus, the harvest of the PL tendon may be unfavorable to throwing athletes. In addition, a potential disastrous complication of PL harvest is inadvertent injury or harvest of the median nerve which has been reported.[4]

For the 20% of patients who do not have a PL tendon, the gracilis or semitendinosus have also been utilized as grafts.[8,23] The hamstring is harvested in a similar fashion when performed for anterior cruciate ligament reconstruction.[8] Risks associated with hamstring harvest include injury to the infrapatellar branch of the saphenous nerve and wound complications. Some studies have demonstrated persistent knee flexion weakness after harvest, leaving some to advocate for harvest from the contralateral leg (ie, landing leg), as this extremity is believed to have less involvement in the overall throwing motion.[8]

Although PL and hamstring tendon autograft options have had clinically favorable results, surgeons may consider donor site morbidity and increased operative time when using these autografts.[9,24] Moreover, a systematic review demonstrated no difference in return to sports time between either graft.[24] Previous biomechanical studies of UCLR techniques have found that neither the PL nor the semitendinosus have been able to reach the biomechanical strength of the native UCL.[15,20] An ideal graft for this procedure would demonstrate favorable biomechanical properties while avoiding potential functional compromise and other risks associated with autograft harvest.

Allograft use may be a potential solution. The plantaris, hamstring, and peroneus longus have been reported in the literature.[18] In a study by Savoie et al,[22] a total of 116 patients with mUCLR using a hamstring allograft reported Conway-Jobe scores as excellent in 80% of patients, good in 13%, and fair for 7%, with no poor outcomes. Similar findings were demonstrated in a 25-patient cohort studied by Kennon et al,[13] with mean Summary Outcome Determination scores of 9 and Timmerman-Andrews scores of 97 at 8 years after mUCLR with plantaris, split semitendinosus, or peroneus longus allograft.

In this biomechanical study, we investigated the fresh-frozen knee medial collateral ligament (kMCL) allograft as a potential graft option for UCLR. The kMCL graft was selected because it is structurally similar to native mUCL tissue. Moreover, the graft was felt to be long enough to provide a reconstructive alternative to previously described techniques. The primary aim of the study was to compare the kMCL allograft with the PL autograft in terms of kinematics and load to failure after UCLR in human donor elbow specimens. We hypothesized that there would be no significant difference in these biomechanical properties between the kMCL allograft and the traditionally used PL autograft.

METHODS

Specimen Preparation

Institutional review board approval was not required for this laboratory investigation utilizing deidentified human donor specimens. Twelve matched pairs of fresh-frozen all male cadaveric upper extremities with a mean age of 52 ± 11 years (range, 30-64 years) were procured from an institute-approved tissue bank and stored at −20°C. Specimens were examined for abnormalities or evidence of previous injury to the medial distal humerus, proximal

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Ethical approval was not sought for the present study.

ulna, flexor-pronator mass, native mUCL, sublime tubercle, or joint capsule. The matched pairs were divided into alternating laterality groups: (1) UCLR performed with a PL autograft and (2) UCLR with an aseptically processed kMCL allograft.

Specimens were thawed overnight at room temperature before dissection. Then, elbows were prepared for UCLR and biomechanical testing. First, an ipsilateral PL tendon graft was harvested from all specimens. The skin and subcutaneous tissue of the medial aspect of the elbow were dissected off, and the flexor carpi ulnaris muscle split to reveal the underlying mUCL. Next, the forearm was sectioned transversely 12 cm from the ulnohumeral joint line. Skin and soft tissue were removed to allow rigid fixation in a metal pot in neutral forearm rotation with a 2-part epoxy resin (Smooth-Cast 300; Smooth-On). Motion tracking diode sensors were attached to the humerus and ulna in line with the long axis of the bone (0.1 mm accuracy and 0.01 mm resolution; Optotrak Certus, Northern Digital Inc).

UCL Reconstruction

After each specimen underwent kinematic testing with the native mUCL, an mUCL tear was simulated by creating a longitudinal split over the ulnohumeral joint line and extended distally in line with the fibers of the mUCL with a scalpel. The distal extent of the mUCL was then elevated off of its insertion at the sublime tubercle using a freer, creating a full-thickness mUCL tear. This was followed by kinematic testing of the deficient state, and subsequent UCLR was performed. The elbow was placed at 30° of flexion, and the ulna was then prepared for graft passage using the docking technique.[3] Two 3.5-mm converging tunnels were drilled at the sublime tubercle using a mUCL ulnar guide (Arthrex). These were placed at the anatomic insertion of the native mUCL ligament, visualized at the time of transection, and reconstructed before testing. Next, a 4.5-mm humeral tunnel (docking tunnel) was drilled at the anatomic footprint of the proximal portion of the anterior bundle of the mUCL. This was done over the anteroinferior aspect of the medial epicondyle and directed 30° cephalad.

Both the PL and kMCL allografts were subsequently prepared for reconstruction. Twelve matched pairs of fresh-frozen kMCL allograft specimens were obtained from a soft tissue bank (Musculoskeletal Tissue Foundation Biologics) and stored at −20°C before use. The mean age of allograft donors was 26 years; all donors were men. The kMCL grafts were received as a single packaged specimen with superficial and deep components without a bony attachment. All kMCL allografts required a minimum length of 110 mm or were otherwise discarded. The graft specimens were thawed overnight at room temperature before testing.

Soft tissues on the kMCL graft were debrided, and the graft was cut longitudinally so that it could pass through a 3.5-mm sizer with ease (Figure 1). The graft was not tubularized. A 2-0 looped polyblend suture (FiberLoop; Arthrex) was then whipstitched through each graft limb before bone tunnel passage (Figure 2). The graft was passed through the ulnar tunnel, and attention was turned toward docking, where the graft was subsequently passed into a 4.5-mm humeral docking tunnel positioned at the isometric point. The anterior and posterior limbs were tied over a bone bridge of at least 1.5 cm at the posteromedial humeral condyle with the elbow at 30° of flexion, and varus stress was maintained during graft tensioning. The excess graft was trimmed.

Figure 1. Grafts used for the study include the palmaris longus autograft (top) and the knee medial collateral ligament allograft (bottom).

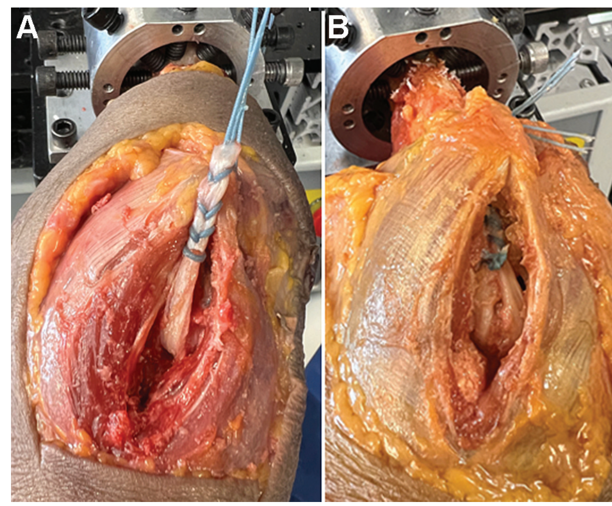

Figure 2. (A) kMCL allograft preparation after passage through the ulnar tunnel. (B) Completed UCLR with a kMCL allograft. kMCL, knee medial collateral ligament; UCLR, ulnar collateral ligament.

For elbows undergoing reconstruction with the PL tendon, the autograft was prepared and passed similarly for the kMCL after being harvested from the ipsilateral forearm. All kMCL and PL grafts were sized to 3.5 mm, pretensioned to 68 N during specimen preparation, and kept moist with saline-soaked gauze.

Kinematic Testing

Elbow kinematics were tested using a previously described method.[6,18,19] Briefly, the humerus was clamped parallel to

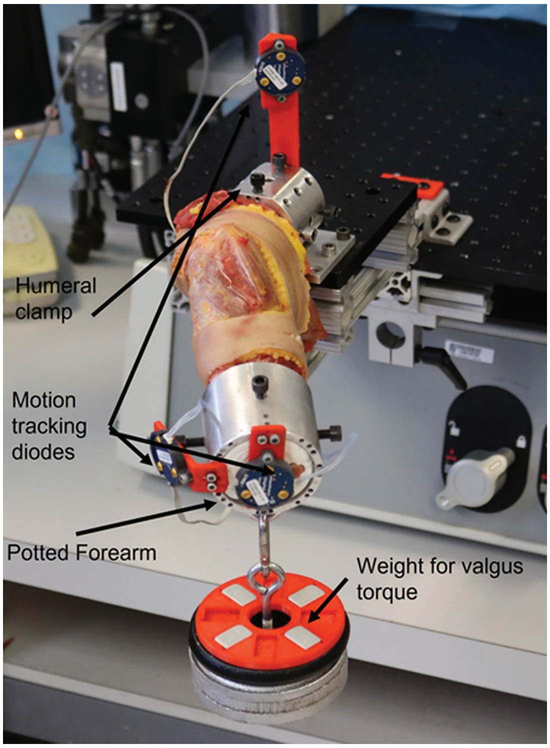

Figure 3. Kinematic testing setup. The humerus was clamped, and weights were added to the pot on the distal forearm to create a valgus load. Motion-tracking diodes were attached to the humerus and distal forearm. Each elbow was rotated from 10° to 120° of flexion, while valgus rotation of the forearm was recorded with respect to the fixed humerus.

the testing surface, and weights were attached to the potted forearm to create a 3-N·m valgus torque on the elbow (Figure 3). Each specimen was manually cycled through its full range of flexion 5 times, and the valgus rotation of the ulna relative to the humerus was recorded at a rate of 128 Hz via a motion tracking system (Northern Digital Inc). Specimens were repeatedly tested 3 times: first with the native mUCL (intact state), after resection of the mUCL (deficient state), and again after reconstruction with either a PL autograft or a kMCL allograft (reconstructed state).

Failure Testing

After kinematic testing, the reconstructed specimens were mounted onto the frame of a biaxial hydraulic testing machine (370.02 Bionix Testing System; MTS Systems Corp) for failure analyses. The humerus was fixed to the frame of the materials testing system with the elbow at 70° of flexion. The potted forearm was attached to the actuator of the testing machine and loaded in valgus at a rate of 0.5 mm/s while load and displacement data were continually recorded. The maximum force recorded was defined as the failure load, and the ultimate torque was calculated at the elbow, as previously described.[6,18,19] Afterward, specimens were visually evaluated to determine the mechanism of failure.

Statistical Analysis

One-factor, random-intercepts, mixed-effects models were used to compare valgus rotation during kinematic testing between mUCL states (intact, deficient, and reconstructed) at each discrete flexion angle (from 10° to 120° in 10° increments) and for each UCLR group (kMCL, PL). Pairwise comparisons among estimated marginal means for each mUCL state were made using the Tukey method. Similarly, 1-factor, random-intercepts, and mixed-effects models were used to compare the native-subtracted valgus rotation values between paired specimens reconstructed with either the kMCL or PL grafts at each discrete flexion angle. Residual diagnostics were inspected for all models to ensure model fit and that model assumptions were reasonably met. Wilcoxon signed-rank tests were used to compare max torque, torsional stiffness, and toughness during load to failure testing between the kMCL and PL groups. The Fisher exact test was used to compare the failure mechanism between the kMCL and PL groups. $P < .05$ was considered statistically significant for all tests.

Statistical power was considered for this experimental design for the primary valgus rotation endpoint, and a fixed feasible sample size was assumed. Assuming an alpha level of .05, 2-tailed testing, and parametric dependent groups comparisons of means, 12 specimens per technique group is sufficient to detect a between-state effect size of d = 0.91, with 80% statistical power. The statistical software R version 4.1.2 (R Core Team, Vienna, Austria) was used for all plots and analyses.

RESULTS

No gross evidence of abnormality was observed in any specimens upon inspection of the medial distal humerus, proximal ulna, flexor-pronator mass, native mUCL, sublime tubercle, or capsule. The resultant data from all 24 elbows were included in the kinematic and failure analysis.

Kinematic Testing

Transection of the mUCL significantly increased the amount of valgus rotation at every angle of flexion evaluated (10°-120°) in all 24 specimens ($P < .001$) (Figure 4). Reconstruction with either a kMCL allograft or a PL allograft restored valgus stability to significantly more stable levels than the deficient state at every flexion angle except at 10° of flexion for kMCL specimens ($P < .01$). The kMCL and PL groups exhibited significantly higher mean valgus rotation compared with the intact state at 10° to 40° of flexion ($P < .01$). At 50° to 120° of flexion, there was no statistical difference in the mean valgus rotation compared with the intact state in both the kMCL and PL groups. When

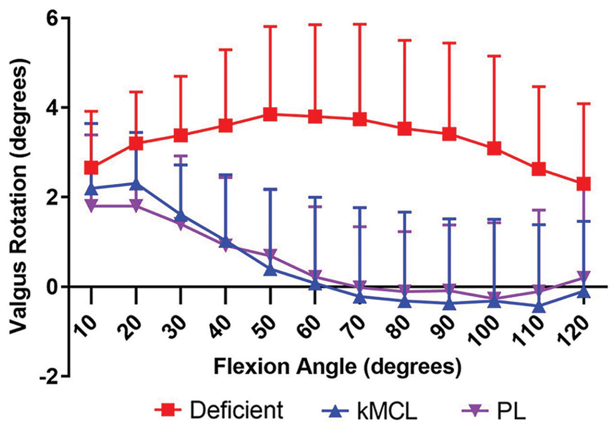

Figure 4. The mean valgus rotation relative to the intact state for mUCL-deficient elbows and after reconstruction with either a PL autograft or a kMCL allograft. Error bars represent standard deviations. kMCL, knee medial collateral ligament; mUCL, medial collateral ligament; PL, palmaris longus.

TABLE 1
Mode of Failure Between the kMCL and PL Graft Groups[a]

Failure Mode	kMCL Graft (n = 12)	PL Graft (n = 12)
Graft-suture interface	6 (50)	1 (8.3)
Graft failure	4 (33.3)	9 (75)
Bone tunnel failure	1 (8.3)	1 (8.3)
Catastrophic failure	1 (8.3)	1 (8.3)

[a]Data are reported as n (%). Group difference for failure mode, P = .051. kMCL, knee medial collateral ligament; PL, palmaris longus.

normalized to their respective intact states, there were no significant differences in valgus laxity between the kMCL and PL groups at any flexion angle.

Failure Testing

The overall failure torque and stiffness for all 24 reconstructions was 18.4 ± 3.6 N·m and 1.46 ± 0.4 N·m/deg, respectively. Elbows reconstructed with kMCL allografts failed at a similar mean torque compared with those reconstructed with PL autografts (18.6 ± 4 vs 18.1 ± 3.4 N·m, respectively; P = .765). Likewise, the torsional stiffness (1.6 ± 0.4 vs 1.3 ± 0.2 N·m/deg; P = .10) and toughness (133.8 ± 49.8 vs 119.4 ± 40.3; P = .32) were not significantly different for the kMCL and PL groups, respectively.

The failure modes were marginally different between the kMCL and PL groups (P = .051) (Table 1). Specimens with PL autografts failed most frequently by graft failure (75%), whereas only 33% of reconstructions with kMCL allografts failed at the graft. Specimens reconstructed with kMCL grafts most often failed at the graft-suture interface (50%) compared with only 1 specimen in the PL group that failed at the interface.

DISCUSSION

In this time-zero biomechanical study, the aim was to evaluate the kinematics and strength of elbows reconstructed with kMCL allografts and compare them with the gold standard PL autografts. There were no significant differences in varus rotation between the grafts from 30° to 110° of flexion. In addition, there were no significant differences in failure torque between the 2 graft groups. The failure mechanism was different between groups, with graft failure being the most common failure mode in elbows reconstructed with a PL graft compared with failure at the graft-suture interface in elbows reconstructed with a kMCL graft.

Cadaveric biomechanical studies have also demonstrated favorable use of allografts. Prud'homme et al[20] tested UCL-reconstructed elbows and compared cycles to failure, stiffness, and elongation of PL autograft versus gracilis, semitendinosus, and patellar tendon allografts and reported no significant difference among all grafts studied. Data in the present study were similar, with no significant differences regarding in situ mechanics between the PL autograft and the kMCL allograft in terms of cycles to failure and stiffness. The most common failure mode in elbows reconstructed with PL autografts was within the graft itself, which parallels the findings of Prud'homme et al,[20] who reported gradual elongation and plastic deformation of palmaris tendon grafts as the failure mechanism for all reconstructed specimens. The most common failure mode found in elbows reconstructed with kMCL allografts—graft-suture interface—may be because of the greater levels of elastin present in ligamentous tissue.

Favorable patient-reported outcomes combined with the resultant data from this and other biomechanical studies suggest that allografts are a viable option for UCLR.[13] While previous studies have focused on the use of hamstring, plantaris, or peroneus longus tendon allografts,[13,22] our work focused on reconstructing the mUCL with the kMCL. This novel graft option may present clinical and biomechanical benefits.

In parallel to the present in situ study, our group also performed uniaxial tensile testing of kMCL and PL graft samples to compare their mechanical viscoelastic properties.[10] The mean yield strain and maximum strain of kMCL samples were significantly greater than that measured for PL samples (P = .03 and P = .02, respectively), while PL samples had greater percentage stress-relaxation.[10] Both graft materials had comparable maximum toughness and demonstrated a similar ability to deform plastically without rupture.[10] This work outlined important differences between tendon and ligament grafts that suggest replacing "like with like" might produce favorable kinematics and clinical outcomes, although further clinical research is needed. Future studies should compare the use of these grafts in relation to mUCL repair with suture tape augmentation, a treatment option also increasingly being implemented for mUCL injury.[1,19]

Complications from allograft use include those inherent to UCLR and range from 6% to 20%; these include wound complications, stiffness, and peri-implant fracture.[13,22]

Other potential risks from allograft use include weakening from sterilization, autoimmune reaction, and potentially delayed healing time.[21] However, these are relatively less severe compared with the potential complication associated with autograft harvest—including donor site morbidity, superficial infection, cutaneous tenderness, potential functional deficits, and inadvertent injury, or harvest of the median nerve.[4,14,26] Thus, with favorable patient outcomes, low complication rates, similar biomechanical profiles, and avoidance of donor site morbidity, allografts demonstrate a safety profile supporting their use in UCLR.

Limitations

The limitations of this study are similar to those of other biomechanical studies. Using harvested fresh-frozen PL did not adequately allow us to assess its performance compared with an in vivo setting. The mean age of specimens tested was higher than that of a patient undergoing UCLR. However, the mean age of our donor tissue was relatively low compared with that of other biomechanical studies,[15,20] and using matched pairs likely limited the effect of age between grafts. Our results were also limited to time-zero after surgery without active muscle contraction and elbow dynamic stability. We did not perform cyclic loading, which might have better replicated the repetitive loading on the mUCL during pitching. However, our testing model followed previously reported methods for testing and comparing UCLR techniques, which include evaluating valgus rotation through a full range of flexion and load to failure.[6,16,18,19] Of note is a discrepancy between the mean age of cadaveric specimens (and resultingly PL autografts) and of the kMCL allograft specimens. This may have introduced another source of bias into our data, although performed according to similar protocols outlined previously.[10]

Despite these limitations, we believe that our study provides important data on an alternative allograft source derived from human knee ligament. Further clinical studies are needed to further elucidate the in vivo safety profile and long-term clinical outcomes of this novel allograft tissue. Future investigation regarding ideal candidates for allograft use and rate of graft incorporation may shed more light regarding the applicability of kMCL in UCLR.

CONCLUSION

Fresh-frozen, aseptically processed kMCL grafts demonstrated similar kinematic and failure properties compared with PL tendon grafts in UCL-reconstructed elbows, although neither graft fully restored kinematics between 10° and 40° of elbow flexion.

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