Original Article

Suture Tape Augmentation Increases the Time-Zero Stiffness and Strength of Anterior Cruciate Ligament Grafts: A Cadaveric Study

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Purpose: To determine the postsurgical strength and stiffness of anterior cruciate ligament (ACL) reconstructions with (ACLR-SA) and without suture tape augmentation (ACLR) in a human cadaveric model. **Methods:** Eight matched pairs of cadaveric knees were tested intact and after bone-patellar tendon-bone ACL reconstruction. Specimens were potted and loaded onto a mechanical testing system, and an anterior drawer force of 88N was applied at 0°, 15°, 30°, 60°, and 90° of flexion. Specimens were then loaded to failure, with clinical failure defined as anterior translation greater than 10 mm. **Results:** ACL-intact knees translated an average of 4.99 ± 0.28 mm across all flexion angles when an 88N anterior load was applied. ACLR knees had significantly greater translation compared to intact specimens. ACLRs with suture augmentation had less of an increase (0.67 mm, 95% confidence interval [CI]: 0.20, 1.14, $P < .01$) than those without suture augmentation (1.42 mm, 95% CI: 0.95, 1.89, $P < .001$). ACLR-SA required greater anterior load (170.4 ± 38.1 N) to reach clinical failure compared to ACLR alone (141.8 ± 51.2 N), $P = .042$. In addition, stiffness of ACLR-SA constructs (23.5 ± 3.3) were significantly greater than ACLR alone (20.3 ± 3.9), $P = .003$. **Conclusion:** Augmentation of ACLR with suture tape allowed full range of motion with improved graft stiffness and increased failure load compared to unaugmented ACLR in this time-zero study. **Clinical Relevance:** Internal bracing may help reinforce ACLR grafts and allow for acceleration of rehabilitation protocols and earlier return to activity.

Anterior cruciate ligament (ACL) grafts reportedly reach their weakest point around 6 to 12 weeks after surgery.[1] This postoperative period is also crucial for rehabilitation to restore motion and improve strength to prevent the development of muscle weakness. The addition of suture tape augmentation for load sharing purposes and protection against failure has

therefore become an appealing option for many surgeons during this vulnerable period. If you can protect the reconstructed graft by improving the graft strength and stiffness, then you may potentially be able to accelerate the patient's rehabilitation. This could potentially avoid delays in the recovery of range of motion and any weakness that may have developed because of the injury or perioperative period.

Suture tape augmentation has previously been described for use in both repairs and reconstructions of extraarticular ligaments throughout the body, including the knee medial collateral ligament,[2] patellar tendon,[3] lateral ankle ligaments,[4] thumb ulnar collateral ligament,[5,6] and the ulnar collateral ligament of the elbow.[7] Biomechanical data suggest that suture tape augmentation improves the strength of these constructs,[3,6,7] and the clinical data show a lower rate of failure in suture-augmented constructs.[4,8] Given that the ACL is an intraarticular ligament, it may behave differently both in the biomechanical and clinical settings. Early in vivo studies in animals, however, have shown that suture does not interfere with bone tunnel healing or lead to prolonged inflammation.[9]
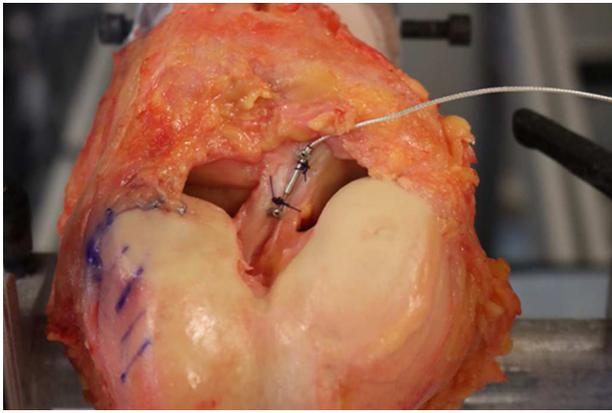
Fig 1. Differential variable reluctance transducer placement with sutures in place in a reconstructed graft in a left knee specimen.

Suture tape augmentation has been described in ACL reconstruction (ACLR) as a novel way to protect the ligament during the healing period and graft maturation phase.[10] Early clinical series have demonstrated improved outcomes in patients with suture-augmented ACLR grafts.[8] There is currently limited biomechanical data available to determine whether suture tape successfully increases the postoperative mechanical strength of an ACLR graft, most of which focuses on ACL repair or its use in animal models and not a human.[11,15]

The purpose of this study was to determine the postsurgical strength and stiffness of ACLR with (ACLR-SA) and without suture tape augmentation (ACLR) in a human cadaveric model. We hypothesized that the use of an isometric suture tape would improve the strength and stiffness of anterior cruciate ligament reconstruction.

Materials and Methods

Specimen Preparation

Institutional review board approval was not required for this laboratory investigation using deidentified cadaveric specimens. Eight matched pairs of cadaveric knee specimens (n = 16, all males) with a mean age of 55.5 ± 4.6 years (range, 47-60 years) were obtained from an institute-approved tissue bank (Science Care, Phoenix, AZ). Each specimen was visually inspected by a fellowship-trained orthopaedic surgeon to confirm no evidence of prior injury, surgery, advanced osteoarthritis, or other gross anatomic abnormalities. Specimens were stored at −20°C and thawed at room temperature 24 hours before testing. All tests were completed at room temperature. The femoral diaphysis and tibial diaphysis were sectioned 20 cm and 15 cm, respectively, from the joint line to maintain a consistent moment arm. The extensor mechanism was completely

removed along with its tibial attachment and saved to prepare the bone patellar tendon bone autograft. The hamstrings were also removed, as well as the muscle compartments of the lower leg. The collateral and posterior cruciate ligaments were preserved along with the capsular tissue adjacent to these structures. The distal portion of the tibia was then potted in an aluminum cylinder.

Before testing, a strain gauge (3 mm stroke microminiature differential variable reluctance transducer [DVRT]; Lord Corp., Williston, VT) was placed within the mid-substance of the ACL (native or graft) with the knee held at 90° of flexion 1 mm proximal to the tibial tunnel/origin. The strain gauge was fixed into the graft via metallic barbs and further secured with 3 separate 3-0 sutures along its length. A 1-2mm notchplasty was made at the intercondylar notch to prevent impingement of sensor with the femur (Fig 1).

Biomechanical Testing

Each knee was placed onto a servo-hydraulic testing machine (MTS Bionix; MTS Corp, Eden Prairie, MN) with the potted tibia attached to the hydraulic actuator and the femur clamped into a pivoting jig that allowed free rotation in the sagittal plane (flexion/extension) (Fig 2). The pivoting jig was locked in placed once the appropriate flexion angle (0°, 15°, 30°, 60°, and 90°) was verified with a digital goniometer. An anterior load was applied to the tibia via the MTS actuator at a rate of 5 N/s until 88 N was reached and held for 15 seconds while strain and anterior tibial displacement were simultaneously recorded using the MTS data acquisition software at a sampling rate of 32 Hz. A load of 88N was chosen based on previous studies that have used an anterior drawer force of 88 N to test ligament laxity.[16,17] The
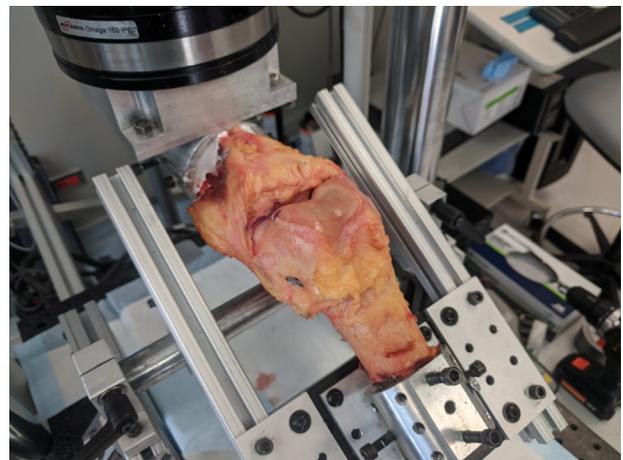

Fig 2. Right knee specimen placed in the MTS device with the tibia potted and attached to the MTS actuator and load cell. The femur is secured in a custom flexion and extension jig.
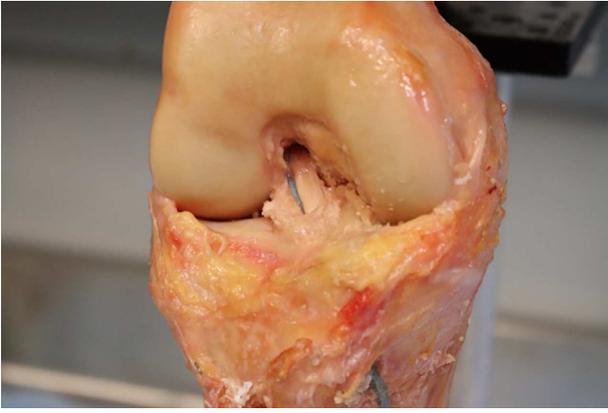
Fig 3. Suture tape augmentation passed colinearly with the anterior cruciate ligament graft in a right knee specimen.

anterior load was cycled 3 times for each flexion state and the average was used for analysis. Specimens were repeatedly tested at 0°, 15°, 30°, 60°, and 90° of flexion in both the intact state and after ACLR. No visible damage to the ACL graft was noted after individual testing angles. Afterward, reconstructed knees were locked into 30° of flexion for failure testing. The tibia was displaced anteriorly at a rate of 10 mm/min until failure occurred. After the first several specimens demonstrated a slow pull through of the bone plug at the interference screw interface, we elected to establish a clinical failure defined as 10 mm of displacement corresponding to a Grade III Lachman's examination. Although bone mineral density was not specifically measured, we noted that some specimens had reduced bone quality that likely played a role in this failure mechanism. The load at 10 mm of displacement was therefore recorded, and stiffness was calculated as the slope of the linear region of the stress-strain curve.

Left and right matched-pair knees were randomly divided in to 2 groups: (1) ACLR without suture tape augmentation (ACLR), and (2) ACLR with suture tape augmentation (ACLR-SA). To preserve tissue integrity all specimens were in saline solution−soaked gauze while testing.

Surgical Technique

ACL Reconstruction

All ACL reconstructions were performed in an open fashion by a single sports medicine fellowship-trained surgeon (S.J.T.). After the intact testing, the ACL was sharply released from its attachments at both the tibial and femoral footprints, taking care to not injure the posterior cruciate ligament, menisci or intermeniscal ligaments. The native ACL was then removed from the specimen while marking the center of the footprint on both the femur and tibia for later tunnel preparation.

BTB Graft Harvest/Graft Preparation. The central 10 mm of the patellar tendon was then harvested with 10×20 mm bone plugs from both the patella and tibial tubercle taken with an oscillating saw. A single drill hole was placed in the femoral bone block perpendicular to the cortical surface to accommodate an Arthrex BTB Tightrope button suspensory fixation device (Arthrex, Naples, FL). Two drill holes were then placed in the tibial bone block, and 2 sutures were placed into each hole for passing and tensioning. A mark was then placed at the transition of the femoral bone plug and tendon for visualization during passage.

Femoral Tunnel Preparation. The native ACL femoral footprint was then identified with the knee flexed to 120° to simulate the position that would be achieved through an anteromedial arthroscopic portal. A spade-tipped drill pin was passed through the center of the ACL femoral footprint between the anteromedial and posterolateral bundles. A 10-mm closed-socket femoral tunnel was made to a depth of 25 mm with a 10-mm reamer.

Tibial Tunnel Preparation. A tibial guide set to 55° was then used to pass a 2.4 mm guide-pin through the center of the tibial footprint of the ACL. With a 10-mm−diameter reamer, the tibial tunnel was established in an outside-in fashion.

Graft Passage and Fixation. The ACL graft was then shuttled through the tibial tunnel and into the femoral tunnel. The femoral button was then passed through the lateral cortex, flipped, and confirmed to be seated firmly on the lateral cortex by pulling tension on the graft. With the tensioning suture, the bone plug was pulled into the femoral tunnel to the previously established mark on the graft. The knee was then cycled, and, while maintaining submaximal distal hand tension and applying a posterior drawer at 30° of flexion, a 9×25 mm titanium metal interference screw (Arthrex) was placed along the anterosuperior cancellous surface of the tibial bone block. Range-of-motion testing was performed to ensure that full range of motion was obtainable.

ACLR-SA

ACL reconstruction in the ACLR-SA group was performed in the same manner with an additional 2mm suture tape passed through the femoral button. These strands were then passed colinear with the graft and positioned in the posterior aspect of the tibial tunnel to avoid being captured by the interference screw (Fig 3). Once confirmed that the suture tape could be tensioned independently the tibia was prepared and tapped for a 4.75 mm anchor. The ends of the suture tape were then fed into the eyelet of the anchor and placed into the tibia at 30° of flexion taking care to not over tighten the
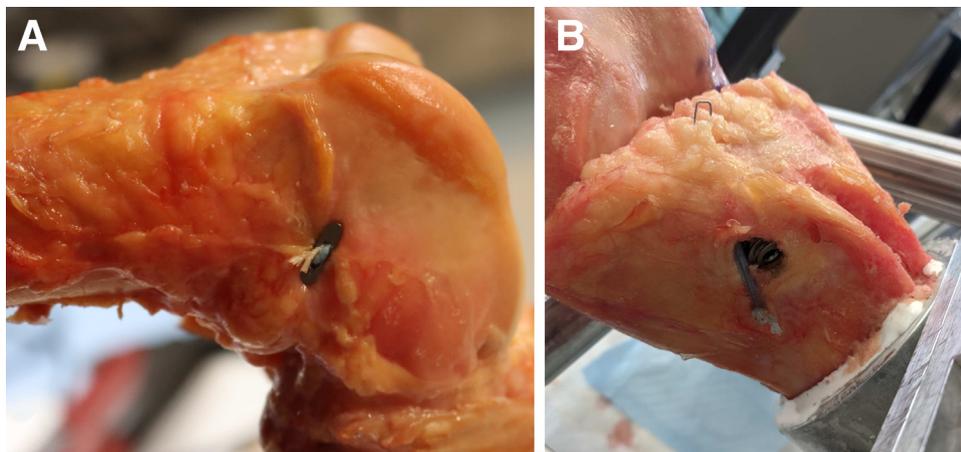
Fig 4. (A) Fixation of the suture tape augmentation through the eyelet of the femoral button in a right knee and (B) independently fixed to the tibia with a suture anchor in a left knee specimen.

construct (Fig 4). Similarly, range of motion was then assessed for full range of motion.

Statistical Analysis

An a priori sample size calculation was conducted using previously reported means and standard deviations[18] for ACL strains, and a 10% difference in strain between groups to determine 8 matched pairs would be required for a power (1-β) of 0.80, with an effect size of 1.0 and alpha set at 0.05. Statistical analysis was performed using SAS statistical software (version 9.4; SAS Institute Inc., Cary, NC). After verification of normally distributed data, a 2-way mixed repeated measures analysis of variance model was used to determine the main effect of each surgical condition (intact, ACLR-SA, and standard ACLR) and each angle of knee flexion on ACL strain and anterior displacement. If the interaction between surgical condition and degree of flexion was significant, further analysis was conducted for each degree tested (0°, 15°, 30°, 60°, and 90°), separately. Tukey-Kramer was used to adjust for multiple comparisons. Student's t-test was used to analyze failure data between reconstructed knees with and without a suture tape augmentation. Significance was set at $P < .05$, and all data are presented as mean ± standard deviation.

Results

There was no gross evidence of abnormality upon inspection of the cruciate ligaments, collateral ligaments, or menisci. The biomechanical data from all 8 knee pairs (n = 16 knees) was reviewed and included in the statistical analysis.

Anterior Drawer Testing

The interaction between surgical conditions (intact, ACLR, ACLR-SA) and flexion angle was not significant, and therefore data is presented as the average across all flexion angles (0°, 15°, 30°, 60°, 90°) tested. ACL-intact knees translated an average 4.99 ± 0.28 mm when an 88N anterior load was applied. ACL-reconstructed knees had significantly greater anterior translation compared to intact knees, both with suture tape augmentation (0.67 mm, 95% confidence interval [CI]: 0.20, 1.14; $P < .01$) and without SA (1.42 mm, 95% CI: 0.95, 1.89; $P < .001$) (Fig 5). Comparing the 2 reconstruction techniques, overall suture augmented ACLRs translated significantly less than those without suture

Fig 5. Average anterior displacement and anterior cruciate ligament (ACL) strain (± standard deviation) for intact and ACL-reconstructed knees, both with and without suture tape augmentation, averaged across all flexion angles. *Asterisk* indicates significant difference from intact, and *dagger* indicates significant difference from ACL reconstruction with suture tape (ACLR-SA). There were no significant differences in strain.
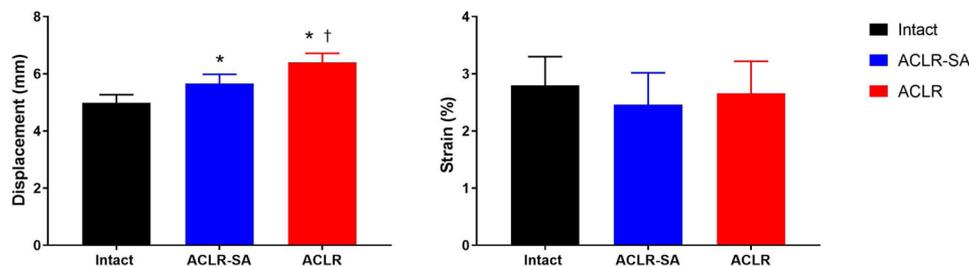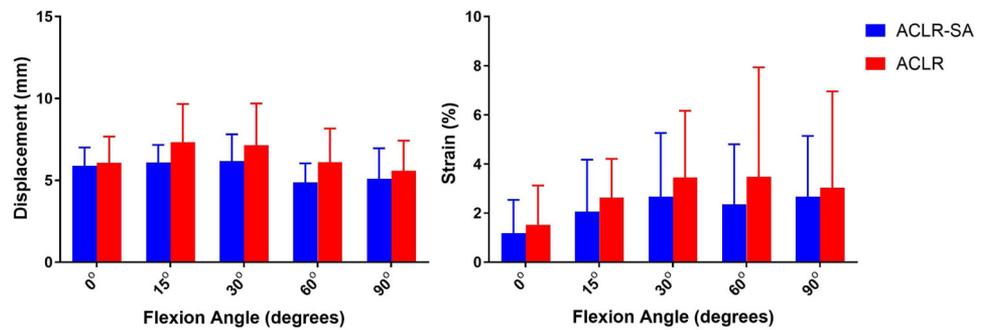
Fig 6. Average anterior displacement and anterior cruciate ligament (ACL) strain (± standard deviation) of ACL-reconstructed knees a function of flexion angle.

tape augmentation (−0.74, 95% CI: −1.39, −0.10; P = .024) across all flexion angles tested. There were no significant differences in strain between intact, ACLR-SA, and standard ACLR. Suture-augmented ACLRs had consistently less translation at each flexion angle tested, but these differences were not significant (Fig 6).

Failure Testing

When loaded to our defined clinical failure, ACL-reconstructed knees without suture tape augmentation failed at an average anterior load of 141.8 ± 51.2 N, which was significantly lower than knees with suture augmented reconstructions (170.4 ± 38.1 N; P = .042) (Fig 7). Suture augmented knees were also significantly stiffer when loaded to failure with an average stiffness of 23.5 ± 3.3 N/mm compared to 20.3 ± 3.9 N/mm for ACLRs without SA (P = .003).

Discussion

The most important finding of this biomechanical cadaveric study at time-zero was that suture tape augmentation increased the stiffness and strength of ACLR grafts when loaded to failure. In addition, specimens with suture-augmented ACLRs consistently recorded lower anterior displacement when an anterior drawer force was applied, although only displacement was significant. This indicates that the suture tape helps protects the graft against excessive anterior motion during physiological loading.

When loaded to clinical failure it was noted that ACLRs without suture tape augmentation failed at an average anterior load of 141 N, which was significantly lower than knees with suture tape augmentation at 170.4 N. These numbers do not represent graft rupture but rather the force on the system when the tibia was displaced anteriorly by 10 mm.

Much of the literature on the use of suture tape augmentation in the ACL is primarily in the context of repair; however, a few studies address reconstruction in tissue-only and animal models. Bachmaier et al[15] used an in vitro model to demonstrate improved failure characteristics of ACL grafts when a suture tape was added to a smaller diameter graft. They found that soft tissue grafts demonstrated reduced elongation at loads of 250 N (38% decrease) and 400N (50% decrease) and higher ultimate load to failure compared to their controls. Similarly, Noonan et al.[19] used a bovine model to demonstrate reduced elongation (56% decrease in tripled grafts, 39% in quadrupled) and increased dynamic stiffness. In their model they used a full construct soft-tissue model with suspensory fixation on the femur and interference screw fixation on the tibial side. Soreide et al.[9] conducted an in vivo assessment of suture tape augmentation in a rabbit anterior cruciate ligament reconstruction model. They found improved biomechanical properties and demonstrated that the suture tape material did not interfere with bone tunnel integration or lead to increased inflammation.
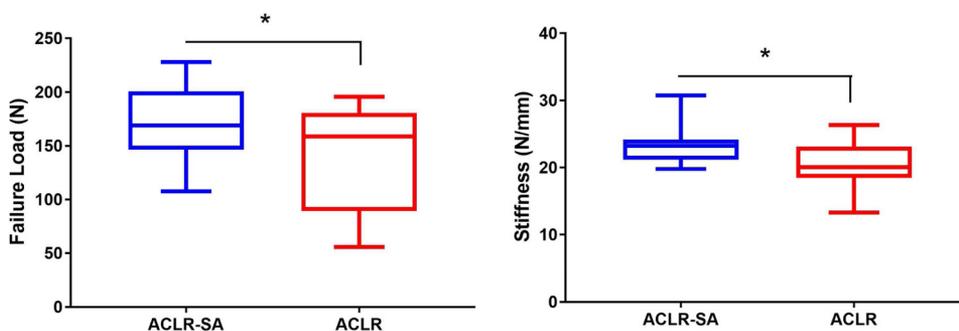

Fig 7. Average load to failure ($P < .05$) and stiffness ($P < .01$) was significantly greater in anterior cruciate ligament (ACL)−reconstructed knees with SA (ACLR-SA) compared to standard reconstructions (ACLR). The *box* extends from the twenty-fifth to the seventy-fifth percentile, the *line* indicates the median, and the *whiskers* represent the minimum and maximum data points.

In the present study we used a full construct human cadaveric model. Although we recognize that arthroscopic reconstruction is the gold standard, performing this open and removing the soft tissue allowed us to eliminate potential variables and isolate the ACL graft and suture augmentation construct as potential contributors to the overall construct stiffness. This certainly does not directly correlate to a clinical scenario but does provide important data on how the suture augmentation effects the constructs' stiffness and therefore potentially improve its ability to resist anterior translation.

Additionally, the addition of suture tape did not prevent the knee from obtaining its full range of motion when independently fixing the sutures to the tibia. If the graft and suture tape are placed too tightly, it is possible to decrease range of motion, which can lead to early graft failure.[20] We used a single hand-pull method to tension the graft, which has shown to be an appropriate method for tensioning bone patellar tendon bone grafts.[20,21] Once the graft is fixed, the suture tape can be placed in a similar manner with similar tension. Other authors have had success with placing a hemostat underneath the suture tape before anchor fixation.[22] Although this can be an effective measure, there are concerns that this could introduce slack to the construct and minimize the benefits of suture augmentation.

The current study did not address concerns about graft abrasion from the suture tape. However, previous studies in the ankle and elbow demonstrate good clinical results with no evidence of early graft failure caused by substance abrasion. Similarly, 2-year clinical studies in the knee have not revealed early graft failure as a complication.[8] Future biomechanical studies that apply cyclic loading to the graft would be required to clarify whether this is a valid concern.

There were no significant differences in ACL strain between knees with suture-augmented and unaugmented ACLRs. This is likely due to difficulties in placing the DVRT device in biological soft tissue. The DVRT relies on precise and consistent placement with little interference as the knee angle is changed. Despite our best effort, it is nearly impossible to place the graft consistently in the same location on every specimen, creating a large standard deviation in strain data. However, because strain is increased with increasing graft elongation, which can indirectly be measured via anterior displacement, we believe it is likely that graft strain decreased when ACLR grafts were augmented with suture tape.

Limitations

Like all cadaveric studies, our data are presented with several limitations. First, the average age of our specimens was 55.5 years, which is higher than the population that usually sustains an ACL tear. This could have implications on bone quality and may have impacted our results, given the use of interference screws for tibial fixation. Additionally, this study characterizes the immediate postoperative state of the knee, was limited to anterior translation, and did not factor in potential elongation of the suture or biological factors that may change the properties of the graft as it matures and undergoes ligamentization. Furthermore, in vivo conditions, including joint compression, dynamic loading, and muscle contraction, were not fully reproduced in this cadaveric biomechanical study. Last, although we demonstrated significant differences between ACLR with and without suture tape, these differences were small and may not translate to clinically relevant differences.

Conclusion

Augmentation of ACLR with suture tape allowed full range of motion with improved graft stiffness and increased failure load compared with unaugmented ACLR in this time-zero study.

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