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Anterior cruciate ligament repair versus reconstruction: A kinematic analysis

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ABSTRACT

Background: The purpose of this study was to compare the biomechanical properties of an anterior cruciate ligament (ACL) anatomic repair of a true femoral avulsion to an anatomic ACL reconstruction. It was hypothesized that the ACL repair and ACL reconstruction would have comparable biomechanical behavior when compared to the native knee.
Methods: Ten paired fresh-frozen cadaveric knees ($n = 20$) were used to investigate knee kinematics when an anterior drawer force, varus, valgus, internal, and external rotational moment were applied at 0, 15, 30, 45, 60, and 90 degrees of flexion. Displacement and rotation were recorded in the following conditions: ACL-intact, ACL-deficient, and ACL-repaired vs reconstructed.
Results: Sectioning of the ACL significantly increased anterior tibial translation (0°, 15°, 30° and 45°) compared to the intact state. The mean anterior displacement difference from intact was lower in the ACL-repaired knees compared to reconstructed knees at 30° and 90°. There were no significant differences between conditions in varus, valgus, internal, or external rotations.
Conclusion: ACL repair and ACL reconstruction procedures restored knee anterior tibial translation in matched paired specimens. There were no differences in valgus, varus, internal, or external rotation. Although, ACL-repaired knees (avulsion model) demonstrated less anterior tibial translation when compared to ACL-reconstructed knees, this difference was less than one millimeter. Based on the findings of this study, repair and reconstruction procedures both restored anterior tibial translation in matched-pair specimens. This suggests that the initial functionality of both techniques is similar and that further clinical studies are needed to compare the long-term stability.

1. Introduction

Anterior cruciate ligament (ACL) reconstruction (ACLR) continues to be associated with excellent functional results and a high rate of return to sport [7,18,20], but there remains some concerns regarding donor site morbidity, postoperative muscular weakness, and development of osteoarthritis secondary to loss of proprioception and failure to restore native biomechanics [3,8]. A randomized controlled trial by Barenius et al. [1] reported 57% of ACLR cases developed osteoarthritis at a 14-year follow-up on the

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operative knee, compared to 18% in the contralateral knee. This three-fold increase in osteoarthritis (OA) is a large economic burden on our national health system. It was recently estimated that 12% of symptomatic OA cases are due to post-traumatic osteoarthritis (i.e., after an ACL injury), resulting in over three billion dollars of US healthcare expense in the U.S. annually [4,37]. This suggests there is a need for improved post-operative ACLR outcomes, especially when considering that most patients who sustain ACL tears are young and otherwise free of the risk factors associated with the development of OA [12].

With an increased knowledge of surgical technology and the biological aspects of ACL healing, there has been renewed interest in the development of treatment techniques, including ACL repair in a specific subset of patients to prevent degenerative changes in a selected group of ACL injuries. This subset includes patients with an acute, femoral avulsion tear with minimal retraction and good tissue quality [24,28]. ACL repairs might provide several advantages over reconstruction if they are successful, including the preservation of the native anatomy (insertion sites and multiple bundle morphology, nerves, and intrinsic cell populations) as well as some of the complex biomechanical properties of the ligament [30]. Preserving the ligament's proprioception, might confer protection to the knee [21,28]. Despite the recent increase in literature surrounding ACL repair techniques, there is currently limited data on the biomechanical changes that a knee undergoes after an ACL repair. Therefore, the purpose of this study was to determine the time-zero biomechanical properties of the knee after an ACL anatomic repair [femoral avulsion] and compare it to an anatomic ACLR. It was hypothesized that ACL-repaired knees and ACL-reconstructed knees would have similar kinematics when compared to the native knee.

2. Materials and methods

2.1. Specimen preparation

Institutional review board approval was not required for this laboratory investigation utilizing de-identified cadaveric specimens. The cadaveric specimens were obtained from a tissue bank and had been donated for the purpose of medical research. Ten paired ($n = 20$) male cadaveric lower limbs, mean age 58.6 years ($\pm$7.0, range, 44–67), were utilized for this study. Specimens without evidence of prior injury, surgical history, or gross anatomic abnormality were selected. Specimens were stored at -20 °C and thawed at room temperature for 24 h prior to preparation. The femoral diaphysis was sectioned 20 cm from the joint line; all soft tissues within 10 cm of the joint line were preserved, and the remaining soft tissues were removed. Three threaded hooks were secured bi-cortically in the tibial diaphysis, oriented perpendicular to the tibial shaft. The first was placed 10 cm distal to the joint line and directed anteriorly; the second 15 cm distal to the joint line and directed laterally; and the third 20 cm distal to the joint line and directed medially. Care was taken to measure and ensure each hook was properly positioned and consistently placed in the same location, perpendicular to the anatomical axis of the femur, throughout all specimens.

2.2. Biomechanical testing

For testing, specimens were loaded onto a custom apparatus with the femur rigidly secured and the ankle held in a frame that would accommodate knee flexion angles from 0° to 90°. Positional data of the tibia relative to the femur during static loading

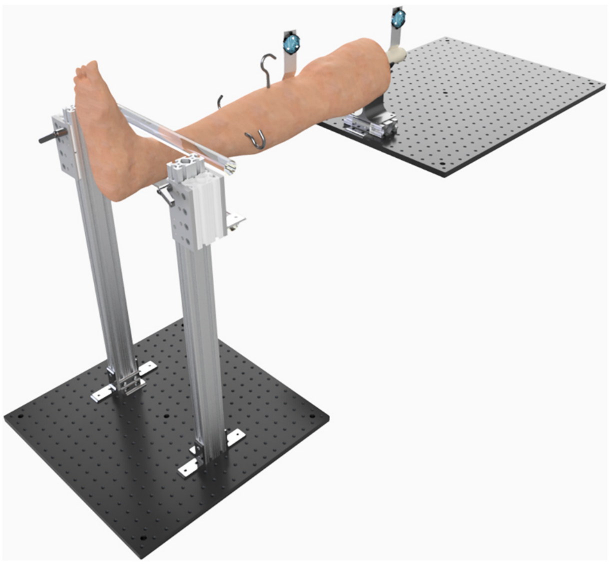

Figure 1. Illustration of a right lower extremity mounted in the testing device with tibial hooks for the application of force, and infrared motion tracking diodes to record relative motion.

were obtained with an optical imaging system using diodes attached to the femur and tibia per manufacturer's specifications (0.1 mm accuracy and 0.01 mm resolution; Optotrak Certus, Northern Digital Inc.; Waterloo, Ontario, Canada). Figure 1. The anatomic axis of the femur and the mechanical axis of the tibia were used as defined by the International Society of Biomechanics standard for joint kinematics [6,44].

Specimens were cyclically pre-loaded anteriorly to remove viscoelastic effects. Afterwards, each knee was statically loaded through the previously placed threaded bicortical screws to produce: a 100-N anterior drawer force, five-Newton-meter varus force, five-Newton-meter valgus force, five-Newton-meter internal rotation, and five-Newton-meter external rotation, as previously described [38]. Each load condition was held for 15 s using an S-beam load cell (LCCA-100, OMEGA Engineering Inc.; Stamford, CT), during which a 10-second period of motion tracking and load cell data was recorded at a rate of 128 Hz, the average of which was used for data analysis. These loads were repeated at 0°, 15°, 30°, 45°, 60°, and 90° of knee flexion, starting with the knee in a neutral position, verified by the motion tracking cameras.

The loading sequence was repeated for each specimen in the following ligamentous states: (1) ACL-intact, (2) ACL-deficient, (3) either ACLR or ACL repair based on random assignment for each of the paired knees. All surgeries were performed by two sports medicine, board certified orthopedic surgeons (initials blinded for review). The sequence of flexion angles was alternated, and specimens were tested in a random order to ensure matched-pairs were not tested sequentially. In addition, surgeons were blinded to the testing order to prevent bias. To preserve tissue integrity all specimens were wrapped in saline soaked gauze whenever possible.

2.3. Surgical technique

A medial parapatellar arthrotomy was performed and the menisci, cartilage, and cruciate ligaments were examined to evaluate for any pathology. After identification of the relevant structures, sectioning, and surgical procedures, soft tissue and skin incisions were closed prior to each testing state with staples and the biomechanical testing protocol was performed to record the kinematic pattern of the intact state of each specimen. Next, the ACL was sectioned on the femoral attachment and the arthrotomy was then similarly repaired. The testing protocol was then performed to record the kinematic pattern of the ACL deficient state. After the ACL-deficient state was tested, within each pair, one knee was randomly assigned to an ACL repair procedure, and the other knee to an ACLR. All ACL repairs and ACLRs were performed by two orthopedic surgeons (*initials blinded for review*).

2.3.1. Anterior cruciate ligament reconstruction

An anatomic single-bundle ACLR using a bone-patellar tendon-bone (BTB) autograft were performed according to previously reported technique [32]. BTB bone plugs were sized to 10 mm in diameter and 25 mm in length. The native ACL tibial and femoral footprints were visually identified with the knee flexed to 120° in the biomechanical testing device system. A seven millimeter over-the-top guide was used to anatomically position the femoral ACL tunnel in reference to the posterior wall of the lateral femoral condyle and the lateral intercondylar ridge. An eyelet guide-pin was passed through the center of the ACL femoral footprint, between the anteromedial and posterolateral bundles and a 10-mm closed-socket femoral tunnel was reamed at 120° of knee flexion with a 10-mm low-profile reamer (Arthrex Inc.) to a depth of 25 mm which simulated the reaming position that would be achieved through an accessory anteromedial arthroscopic portal.

Then, an ACL aiming device (Arthrex Inc.) was used to pass an eyelet guide-pin through the center of the tibial footprint of the ACL. The tibial tunnel was then reamed outside-in with a 10-mm diameter cannulated reamer. The ACL graft was then positioned and fixed in the femur with a 7 × 20 mm cannulated interference titanium screw (Arthrex Inc.). The ACL graft was passed

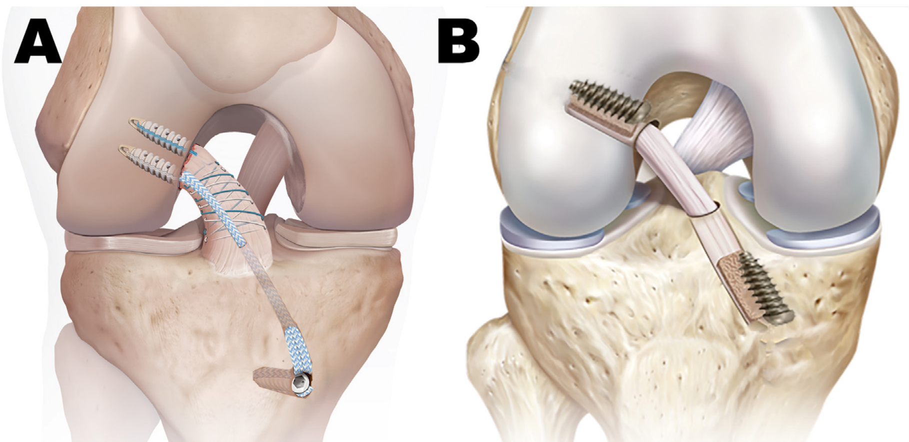

Figure 2. Illustration of an (A) ACL repair and a (B) ACL reconstruction techniques on a right knee.

through the tibial tunnel and fixed in full extension with a titanium cannulated interference screw 9 × 20 mm (Arthrex Inc.) while applying a distal traction force of 88 N. The arthrotomy was closed with staples Figure 2.

2.3.2. Anterior cruciate ligament repair

The anteromedial and posterolateral bundles of the ACL were identified. The sutures were passed through the anteromedial bundle using the Scorpion Suture Passer (Arthrex) with a No. 2 FiberWire suture (Arthrex) from the intact distal end in an alternating, interlocking Bunnell-type pattern toward the proximal end as previously described [39]. Four passes were performed until the proximal end was reached. The posterolateral bundle suturing was performed in a similar fashion using a No. 2 TigerWire suture (Arthrex). With the knee at 90° flexion, a 4.5 by 20-mm tunnel was created, into the anatomic attachment of the anteromedial bundle and then tapped. The FiberWire sutures of the anteromedial bundle were passed through the eyelet of a 4.75-mm Vented BioComposite SwiveLock suture anchor (Arthrex) [preloaded with collagen-coated FiberTape (Arthrex) which was then used as the internal brace]. This procedure was then repeated for the posterolateral bundle with the TigerWire sutures and a 3.5-mm Vented BioComposite SwiveLock suture anchor that was inserted at 110° of flexion.

Attention was then turned to fix the internal brace distally. First, an ACL guide was used to drill a 2.4-mm drill pin up through the tibia from the anteromedial cortex and into the center of the ACL tibial insertion. This was then switched for a Straight Microsuture Lasso (Arthrex), and the FiberTape retrieved through the tibia where it was fixed with a 4.75-mm Vented BioComposite SwiveLock suture anchor (Arthrex) on the anteromedial aspect of the knee after cycling the knee and tensioning in full extension. The knee was then cycled ensuring that full range of motion was preserved.

2.4. Statistical analysis

A total of 10 paired knees were chosen based on a power analysis using the results and standard deviations between the intact and ACLR in Kennedy et al., which suggested a minimum of seven specimens would be required to achieve a power of 0.80 ($\alpha = 0.05$) [19]. Statistical analysis was performed using SAS statistical software (version 9.4, SAS Institute Inc., Cary NC). After verification of normally distributed data for all loading states, a two-way mixed repeated measure model was used to determine the effects of each surgical treatment (ACL-intact, ACL-deficient, and ACL-repaired vs reconstructed) and knee flexion angle on knee kinematics. If the interaction between treatment and degree was significant, further analysis was conducted for each degree tested (0°, 15°, 30°, 45°, 60°, 90°), separately. Tukey–Kramer was used to adjust for multiple comparisons. Significance was set at $p < .05$ and all data are presented as mean ± standard deviation.

3. Results

There was no gross evidence of abnormality upon inspection of the cruciate ligaments, menisci, or cartilage. The ACL and secondary stabilizing structures were intact in all pairs. No knee damage or graft failure was observed during testing. The data from all 10 knee pairs (n = 20 knees) was reviewed and included in the analysis.

3.1. Anterior tibial translation

In ACL-intact knees, a 100-N anterior load resulted in a mean displacement of 3.2 ± 2.3 mm at 0° of knee flexion. Peak intact anterior displacement of 5.4 ± 2.6 mm was recorded at 15° of flexion, followed by 30° of flexion (5.1 ± 1.9 mm), which

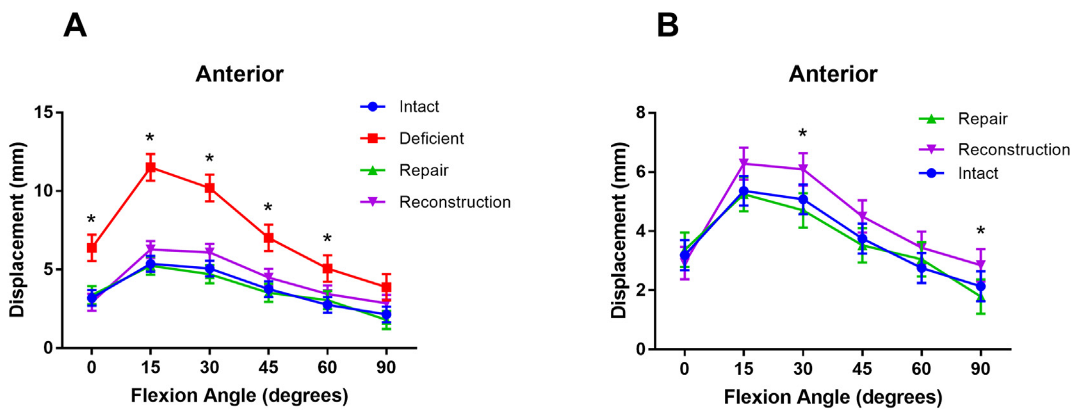

Figure 3. (A) Anteroposterior laxity as a function of knee flexion angle for all treatments. Sectioning of the ACL resulted in higher anterior displacement compared to intact, *indicates $p < .05$ compared to intact state. (B) ACL-repaired knees demonstrated greater stability compared to reconstructed knees at all angles except 0 degrees, which reached significance at 30 and 90° of knee flexion, *$p < .05$.

continued to decrease as function of flexion angle, Figure 3A. Sectioning of the ACL resulted in a significant increase in displacement compared to intact at every angle, except 90° of knee flexion ($p = .08$). Subsequent reconstruction of the ACL restored normal anterior translation at 0°, 15°, 30°, and 45°, with an average displacement of 6.3 ± 2.5 mm and 6.09 ± 1.4 mm, at 15° and 30° respectively. Repair of the ACL also restored stability to knees at 0°, 15°, 30°, 45°, and 60°, with an average displacement of 5.3 ± 2.0 mm and 4.7 ± 1.8 mm, recorded at 15° and 30° respectively. ACL-repaired knees demonstrated improved stability displacement values closer to intact compared to ACL-reconstructed knees, which reached significance at 30° and 90° of knee flexion, Figure 3B.

3.2. Internal and external rotation

Average peak internal rotation among ACL-intact knees was 16.8 ± 4.2° recorded at 30° of knee flexion. Sectioning the ACL did not result in a significant increase in internal rotation. Likewise, reconstruction and repair of the ACL did not significantly change the amount of internal rotation from ACL-intact or -deficient knees at any of the flexion angles tested, Figure 4.

There were no significant differences in external rotation among the four different treatments (ACL-intact, -deficient, -reconstructed, or -repaired), Figure 5A. Mean external rotation in ACL-reconstructed knees was on average 2.1° higher than ACL-repaired knees, across all angles, with a peak difference of 3.5° at 15° of knee flexion ($p = .09$), Figure 5B.

3.3. Varus and valgus forces

ACL-intact knees rotated an average of 2.2 ± 0.2° when a five-Newton-meter varus moment was applied across all flexion angles (0–90°) tested. ACL-deficient knees did not demonstrate a significant increase in varus laxity compared to ACL-intact knees, with a varus rotation of 2.3 ± 0.4° averaged across all flexion angles. ACL-reconstructed knees and ACL-repaired knees rotated an average 2.4 ± 0.5° and 2.2 ± 0.4°, respectively across all flexion angles, demonstrating little variance across all four treatment groups, Figure 6A.

When a five-Newton-meter valgus moment was applied to ACL-intact knees at 0° of flexion it resulted in 0.8 ± 0.4° of rotation, which gradually increased with an increasing angle of flexion to 2.3 ± 1.2° at 90° of flexion. ACL-deficient, -reconstructed, and -repaired knees did not demonstrate any significant differences in valgus rotation at any of the knee flexion angles tested, Figure 6B.

4. Discussion

The main findings of this study support the hypothesis that both an anatomic ACLR and ACL repair (when ACL is avulsed from the femur) effectively restore anterior knee laxity after ACL injury to a near native state. ACL repair did demonstrate reduced anterior tibial translation compared to ACLR at 30 and 90°, but on average this difference was less than a millimeter across all angles of flexion. This suggests that both procedures have similar post-operative functionality, and that further research that stratifies the short- and long-term clinical risks and benefits are of utmost importance in the specific subset of patients where a repair can be performed.

The ACL is the primary restraint to anterior tibial translation in resisting up to 87% of the anterior tibial force [5]. Previous literature reported that there were no significant differences in internal rotation torsion between ACL-intact and ACL-deficient specimens (only with knee abduction torque) [2]. However, an in vivo study, Hoshino et al. [15] observed reduced anterior tibial translation and increased knee rotation in ACL reconstructed knees compared to the contralateral knees (mean of two-millimeter difference). Despite extensive research on ACLR kinematics, biomechanical data on ACL repairs is currently lacking. ACL repairs demonstrating a better kinematic control was suggested by Murray et al. who a trend ($p = .068$) of reduced macroscopic cartilage damage in ACL repaired knees compared to conventional ACLR in a porcine model at 12 months [25]. This is supported by initial studies that indicate early intervention and patient selection may improve healing and the biomechanical properties of

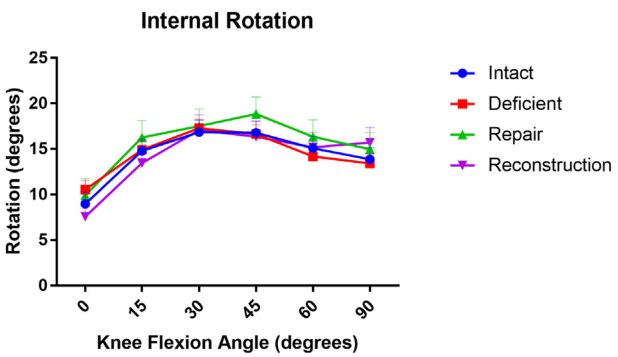

Figure 4. Internal rotation as a function of flexion angle, demonstrating no statistical differences in rotation between treatments.

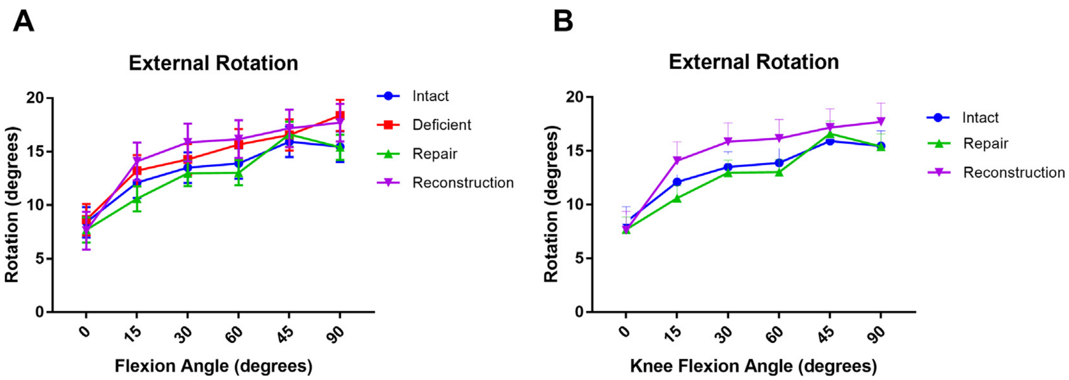

Figure 5. There was no significant difference in tibial external rotation between the four treatment groups (A), although ACL-repaired knees more closely matched the kinematic pattern of intact-knees compared to ACL-reconstructed-knees (B).

repaired ACLs in carefully chosen patients [27,33]. Additionally, preserving one bundle if intact (single anteromedial bundle biological augmentation) has been reported to result in improved clinical and functional outcomes between baseline and follow-up at a minimum of 24 months which demonstrates the importance of preserving native proprioception [29].

Improved clinical outcomes after ACL repairs are increasingly being reported in the literature. Mackay et al. [22] reviewed 68 consecutive patients who underwent ACL repair with an internal brace ligament augmentation and reported comparable early results to ACLR, with the greatest improvement in return to sport activity [22]. Recently, Difelice et al. [11] performed a retrospective review with early follow-up of 11 consecutive cases of ACL primary repair with a separate anchor fixation for each bundle. Patients were included if they had a proximal avulsion tear and excellent tissue quality confirmed via arthroscopy to be adequate for repair. Ten out of 11 patients had good subjective and objective outcomes after ACL repair surgery at a mean follow-up of 3.5 years. Murray reported that ACL repairs augmented with an extracellular matrix scaffold produced similar outcomes to ACLR with a hamstring autograft at two years with significantly higher hamstring strength on the repair group [26]. On the contrary, a recent study comparing ACL repair versus reconstruction on adolescent (seven to 18 years old) patients by Gagliardi et al. [13] reported a 48.8% cumulative incidence of graft failure in the first 3 years after surgery in the repair group, as opposed to 4.7% in the reconstruction group. These studies all demonstrate the need for further research to develop a very stringent set of indications for this procedure as ACLRs are reported to achieve high rates of satisfaction [9]. Outcome studies show that after ACLR, 81% of individuals return to sports, 65% return to their preinjury level, and 55% return to competitive sports with a retear rate of 5.8% [34]. Furthermore, over 90% of children and adolescents return to sport after an ACLR according to a recent meta-analysis [17].

There were several limitations associated with this study. It is recognized that this was a time-zero study with surgically created defects that may not fully reflect the laxity and fraying associated with acute injuries of soft tissue attenuation that may occur in chronic injuries. As such, this study setup represents the best-case scenario of a true femoral ACL avulsion. In addition, we were unable to distinguish whether the use of an internal brace in the ACL repair contributed to improved anterior translation of if it was a product of the repair itself. The internal brace may alter overall healing in a clinical setting. In addition, the mean age of specimens used in this study was higher than the population that usually sustains an ACL tear. Further, in vivo conditions, including joint compression, dynamic loading, and muscle contraction was not fully reproduced in this cadaveric biomechanical study. Alternatively, strengths of this study include: a relatively large sample size of all male matched-pair specimens to limit

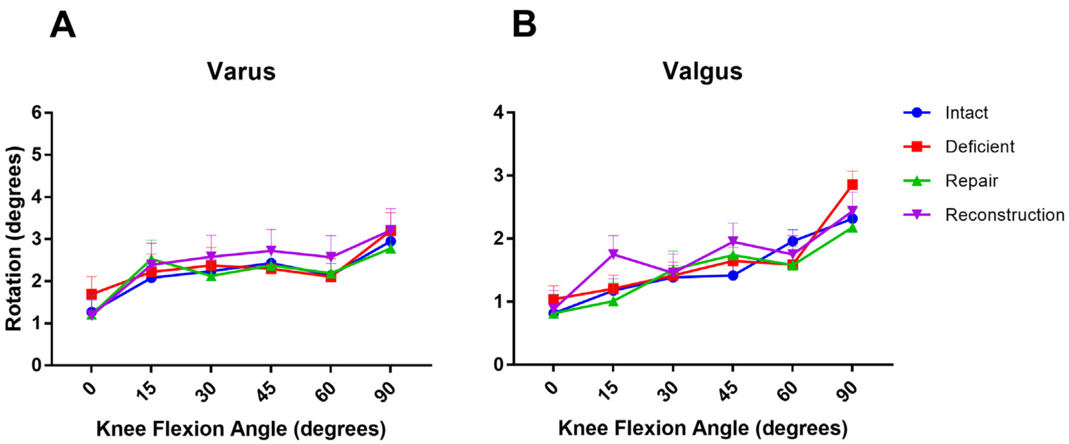

Figure 6. Coronal plane motion of the knee. There was no significant difference in varus (A) or valgus (B) rotation when a five-Newton-meter moment was applied to the tibia.

variability, use of a reproducible and previously validated protocol, and blinding of the surgeon to the specimen order and pairing to limit any potential bias.

5. Conclusion

ACL repair and ACLR procedures both restored knee anterior tibial translation in matched-pair specimens. ACL-repaired knees (avulsion model) demonstrated less anterior tibial translation compared to ACL-reconstructed knees, although the clinical relevance of this finding, which equates to an average difference of less than one millimeter, should be taken with caution as further research comparing these two techniques becomes available.

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