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An In Vitro Robotic Assessment of the Anterolateral Ligament, Part 2

Anterolateral Ligament Reconstruction Combined With Anterior Cruciate Ligament Reconstruction

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Background: Recent biomechanical studies have demonstrated that an extra-articular lateral knee structure, most recently referred to as the anterolateral ligament (ALL), contributes to overall rotational stability of the knee. However, the effect of anatomic ALL reconstruction (ALLR) in the setting of anterior cruciate ligament (ACL) reconstruction (ACLR) has not been biomechanically investigated or validated.

Purpose/Hypothesis: The purpose of this study was to investigate the biomechanical function of anatomic ALLR in the setting of a combined ACL and ALL injury. More specifically, this investigation focused on the effect of ALLR on resultant rotatory stability when performed in combination with concomitant ACLR. It was hypothesized that ALLR would significantly reduce internal rotation and axial plane translation laxity during a simulated pivot-shift test compared with isolated ACLR.

Study Design: Controlled laboratory study.

Methods: Ten fresh-frozen cadaveric knees were evaluated with a 6 degrees of freedom robotic system. Knee kinematics were evaluated with simulated clinical examinations including a simulated pivot-shift test consisting of coupled 10-N·m valgus and 5-N·m internal rotation torques, a 5-N·m internal rotation torque, and an 88-N anterior tibial load. Kinematic differences between ACLR with an intact ALL, ACLR with ALLR, and ACLR with a deficient ALL were compared with the intact state. Single-bundle ACLR tunnels and ALLR tunnels were placed anatomically according to previous quantitative anatomic attachment descriptions.

Results: Combined anatomic ALLR and ACLR significantly improved the rotatory stability of the knee compared with isolated ACLR in the face of a concurrent ALL deficiency. During a simulated pivot-shift test, ALLR significantly reduced internal rotation and axial plane tibial translation when compared with ACLR with an ALL deficiency. Isolated ACLR for the treatment of a combined ACL and ALL injury was not able to restore stability of the knee, resulting in a significant increase in residual internal rotation laxity. ALLR did not affect anterior tibial translation; no significant differences were observed between the varying ALL conditions with ACLR except between ACLR with an intact ALL and ACLR with a deficient ALL at 0° of flexion.

Conclusion: In the face of a combined ACL and ALL deficiency, concurrent ACLR and ALLR significantly improved the rotatory stability of the knee compared with solely reconstructing the ACL.

Clinical Relevance: Significant increases in residual internal rotation and laxity during the pivot-shift test may exist in both acute and chronic settings of an ACL deficiency and in patients treated with isolated ACLR for a combined ACL and ALL deficiency. For this subset of patients, surgical treatment of the ALL, in addition to ACLR, should be considered to restore knee stability.

Keywords: anterolateral ligament; anterior cruciate ligament; reconstruction; rotational instability; pivot shift; robotics

Current anterior cruciate ligament (ACL) reconstruction (ACLR) techniques focus on anatomic graft placement in an effort to restore native knee kinematics. However, historically, many surgeons were primarily concerned with restoring rotational stability[50] and advocated for extra-articular "lateral plasty" or "tenodesis" techniques.[1,10,22,26,32,33] Mixed biomechanical and clinical results with extra-articular procedures and the widespread use of arthroscopic surgery shifted the focus to intra-articular ACLR by the late 1980s.[9,11,42,44,53]

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Single-bundle ACLR became the treatment of choice because of reported improvement in anterior translation and comparable in situ forces to the intact knee.[4,58] Double-bundle ACLR then emerged in response to the criticism that isolated single-bundle ACLR did not sufficiently restore rotational stability.[17,45,58,59] In turn, this led to the development of more anatomic single-bundle ACLR techniques. However, biomechanical and clinical results have been inconclusive in the single- versus double-bundle ACLR debate surrounding rotational stability.[18,37] Goldsmith et al[18] reported that neither anatomic single- nor double-bundle ACLR restored translational or rotational kinematics to the intact state. Moreover, the kinematic difference between the single- and double-bundle ACLR techniques was reported to be clinically insignificant.

Attention has since returned to rotational stability provided by the lateral knee structures, in conjunction with intra-articular ACLR, specifically the structure most recently redefined as the anterolateral ligament (ALL).[7,8,20,43,56] A recent report that up to 25% of patients may have a residual pivot shift after ACLR[51] reaffirms the theory that tears of secondary restraints, such as the ligamentous and capsular structures of the lateral compartment, should be properly recognized and treated.[13] This may potentially explain the importance of the ALL during the pivot shift when it is concurrently injured. However, additional research is needed to determine if the ALL may need to be reconstructed in cases of residual rotatory laxity after ACLR to improve rotational stability. Outcomes after combined intra-articular and extra-articular ACLR are promising. Zaffagnini et al,[60] in a prospective randomized study with a 5-year follow-up, reported better subjective outcomes and sooner return to sport in patients treated with the technique by Marcacci et al[35] when compared with bone–patellar tendon–bone (BTB) and quadruple-stranded hamstring tendon autograft transtibial techniques without lateral plasty. Vadala et al,[55] also in a prospective randomized study, reported a significant reduction in rotational instability for female patients treated with a modified extra-articular MacIntosh procedure in addition to ACLR with hamstrings when compared with ACLR with hamstrings alone. Recently, Sonnery-Cottet et al[51] described promising outcomes at an initial short-term follow-up after combined ACLR and ALL reconstruction (ALLR). At a minimum of 2 years, 91.6% of patients had a negative pivot shift, with significant improvements in Lysholm, subjective International Knee Documentation Committee (IKDC), and objective IKDC scores. However, before surgery, only 27.7% of their patients had a grade 2 pivot shift, and 22.9% had a grade 3 pivot shift.[51] Results from part 1 of this study demonstrated that sectioning the ALL led to significant increases in internal rotation and axial plane translation during a simulated pivot-shift test in the presence of an ACL tear.[48] Although extra-articular tenodesis has been reported to synergistically act with ACLR in controlling the pivot-shift phenomenon,[40] to date, anatomic ALLR has only been hypothetically suggested to improve internal rotation stability and reduce laxity during this test.[8,41,49]

The purpose of this study was to investigate the kinematics of ALLR in the setting of ACLR compared with intact and sectioned ALL states between 0° and 120° of flexion by robotically applying a simulated clinical examination. We hypothesized that concurrent ALLR and ACLR after a combined injury would improve internal rotation stability and axial plane translation during a simulated pivot-shift test compared with isolated intra-articular ACLR.

METHODS

Specimen Preparation

Ten fresh-frozen human cadaveric knees with no prior injury, surgical history, or gross anatomic abnormality (mean age, 49.3 years; range, 41-64 years; all male) were included in this study. Internal review board approval was not necessary to conduct this investigation because deidentified cadaveric specimens are exempt from review at our institution. Specimen preparation and the testing setup utilizing a 6 degrees of freedom robotic system are further detailed in part 1 of this 2-part study.[48]

Biomechanical Testing

Intact, ACLR with ALL-intact, ACLR with ALLR, and ACLR with ALL-deficient knee conditions were tested with a simulated pivot-shift test of combined 10-N·m valgus and 5-N·m internal rotation torques applied at 0°, 15°, 30°, 45°, and 60° of knee flexion.[12,24,25,36] A 5-N·m internal rotation torque and an 88-N anterior tibial load were applied at 0° to 120° of knee flexion in 15° of flexion increments. Randomization of the tested flexion angle order was performed to aid in decreasing any testing bias.

Surgical Technique

A medial parapatellar arthrotomy and a lateral hockey stick–shaped incision were performed before insertion within the robotic system.[48] Before reconstruction testing,

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2 states, intact and ACL deficient, were evaluated, and an ACL+ALL-deficient state was additionally tested following completion of all reconstruction procedures. Reconstructions were performed with the knee fixed inverted within the robotic system to reduce possible testing errors introduced from specimen removal, as previously described.[18,19]

ACL Reconstruction

All ACLRs were performed by a single orthopaedic surgeon (M.N.). Anatomic single-bundle ACLR using a BTB allograft (AlloSource) was performed according to previously reported techniques.[18,54,57] Allograft BTB bone plugs were sized to 10 mm in diameter and 25 mm in length. The native ACL's tibial and femoral footprints were visually identified through a medial parapatellar arthrotomy with the knee flexed to 120° in the robotic system.[18] A 6-mm 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 midpoint of the lateral intercondylar ridge. An eyelet guide pin was passed through the center of the ACL femoral footprint, and a 10-mm closed-socket femoral tunnel, positioned between the anteromedial and posterolateral bundles, was reamed at 120° of knee flexion with a 10-mm low-profile reamer (Arthrex Inc) to a depth of 25 mm,[6] which simulated the reaming position that would be achieved through an accessory anteromedial arthroscopic portal.[15]

A cruciate aiming device was used to pass an eyelet guide pin through the center of the tibial footprint of the ACL.[46,52,62] Particular attention was taken to position the tibial tunnel in its anatomic location with minimal disruption of the anterolateral meniscal root.[28,29] The tibial tunnel was then reamed outside in with a 10 mm–diameter cannulated reamer. Consistency with the manufacturer and reamer type was emphasized during the surgical protocol to minimize aperture variability and tunnel dimensions.[16] The ACL graft was then positioned, and aperture fixation in the femur was performed with a 7 × 20–mm cannulated interference titanium screw (Arthrex Inc). The ACL graft was passed through the tibial tunnel and fixed in full extension with a 9 × 20–mm titanium cannulated interference screw (Arthrex Inc) while applying a distal traction force of 88 N.[3,49]

ALL Reconstruction

ALLRs were performed by a single orthopaedic surgeon (M.N.). The ALL was sectioned at its distal tibial insertion, as described in part 1, based on recent anatomic, radiographic, and biomechanical studies.[7,27,43,48] A guide pin was placed midway between the center of the Gerdy tubercle and the anterior margin of the fibular head (24.7 mm posterior to the center of the Gerdy tubercle and 26.1 mm proximal to the anterior margin of the fibular head) and 9.5 mm distal to the joint line,[27] at the anatomic location of the distal ALL insertion. A 6-mm reamer was used to ream a 25 mm–deep tibial tunnel.

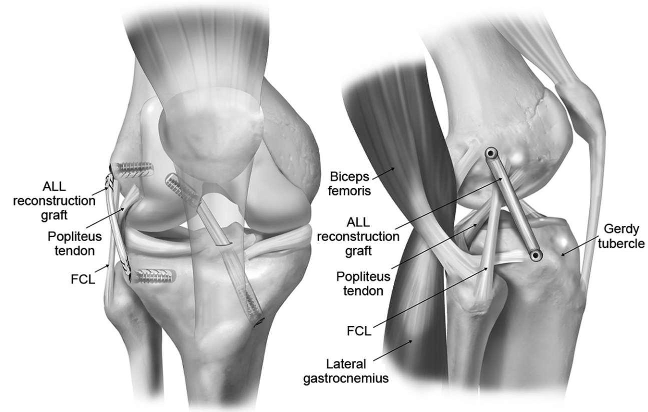

Figure 1. Anterior (left) and lateral (right) views of anterior cruciate ligament reconstruction (ACLR) and anterolateral ligament reconstruction (ALLR) of a right knee. For ACLR, a bone–patellar tendon–bone allograft was sized and fixed within 10-mm femoral and tibial tunnels. A 7 × 20–mm interference screw was used to secure the femoral end of the graft, and a 9 × 20–mm interference screw was used to fix the tibial end with 88 N of traction and the knee positioned in extension. ALLR was performed using a 6 mm–diameter semitendinosus allograft trimmed to 12 cm in length. A 6-mm reamer was used to ream femoral and tibial tunnels at the anatomic attachment sites of the ALL. A 7 × 23–mm biointerference screw was used to secure the graft distally on the tibia, and a similar screw was used to fix the femoral end of the graft under 88 N of tension with the knee positioned at 75° of flexion. ACLR tunnels are not shown in the lateral view. FCL, fibular collateral ligament.

The distal aspect of the fibular collateral ligament (FCL) was identified via a 3-cm horizontal incision into the biceps femoris bursa,[30] and a traction suture was placed in the midsubstance of the FCL to help locate the proximal FCL attachment. Next, the superficial layer of the iliotibial band was split 3 cm over the lateral epicondyle, and tension was applied on the FCL to identify the proximal femoral attachment of the FCL. The femoral attachment of the ALL was identified 4.7 mm proximal and posterior to the FCL's femoral insertion.[27] A 30 mm–deep closed-socket tunnel was reamed with a 6-mm reamer at the femoral attachment of the ALL.

Semitendinosus allografts (AlloSource) were trimmed to 12 cm in length and sized to 6 mm in diameter for the ALL graft. The graft was fixed distally on the tibia with a 7 × 23–mm biointerference screw (Arthrex Inc). The femoral end of the graft was also fixed with a similar biointerference screw while applying 88 N of tension with the knee at 75° of flexion (Figure 1).[43]

Statistical Analysis

Assuming an α level of .0083 (overall α of .05 with Bonferroni correction for 6 comparisons), 10 specimens were found to be sufficient to detect an effect size of d = 1.37

TABLE 1
Axial Plane Translation and Internal Rotation During a Simulated Pivot-Shift Test[a]

	Axial Plane Translation,[b] mm				Internal Rotation,[b] deg			
Flexion Angle	Intact	ALL Intact + ACLR	ALLR + ACLR	ALL Deficient + ACLR	Intact	ALL Intact + ACLR	ALLR + ACLR	ALL Deficient + ACLR
0°	2.0 ± 1.0	2.6 ± 1.0[c,d]	2.5 ± 1.0	2.9 ± 1.2[c,d]	10.0 ± 3.0	10.9 ± 3.4[c,d]	10.8 ± 3.1	11.7 ± 3.6[c,d]
15°	2.7 ± 1.5	3.1 ± 1.8[d]	3.3 ± 1.8	3.7 ± 2.0[c,d]	13.9 ± 4.8	14.6 ± 5.2[c,d]	14.5 ± 4.9	15.6 ± 5.4[c,d]
30°	2.9 ± 1.6	3.2 ± 2.3	3.6 ± 1.9	3.9 ± 2.4	16.4 ± 5.3	16.9 ± 5.3[c,d]	16.5 ± 5.2[e]	18.9 ± 5.7[c,d,e]
45°	2.7 ± 1.9	3.0 ± 2.4	2.8 ± 2.1	3.6 ± 3.0	16.8 ± 5.6	17.3 ± 5.6[c,d]	16.9 ± 5.0[e]	19.8 ± 5.6[c,d,e]
60°	2.5 ± 1.8	3.0 ± 1.9	2.6 ± 1.7	3.8 ± 2.9	16.1 ± 5.2	16.6 ± 5.3[c,d]	16.3 ± 4.4[e]	19.3 ± 4.9[c,d,e]

[a]Values are reported as mean ± SD. ACLR, anterior cruciate ligament reconstruction; ALL, anterolateral ligament; ALLR, ALL reconstruction.
[b]Raw values, unadjusted for flexion angle.
[c]Significant difference from intact ($P < .05$ via a paired t test with Holm adjustment).
[d]Significant difference between ALL intact + ACLR and ALL deficient + ACLR ($P < .05$ via a paired t test with Holm adjustment).
[e]Significant difference between ALLR + ACLR and ALL deficient + ACLR ($P < .05$ via a paired t test with Holm adjustment).

TABLE 2
Anterior Translation in Simulated Anterior Drawer and Internal Rotation During a Simulated Internal Rotation Torque[a]

	Anterior Drawer,[b] mm				Internal Rotation,[b] deg			
Flexion Angle	Intact	ALL Intact + ACLR	ALLR + ACLR	ALL Deficient + ACLR	Intact	ALL Intact + ACLR	ALLR + ACLR	ALL Deficient + ACLR
0°	3.2 ± 0.8	4.1 ± 0.7[c,d]	4.2 ± 0.7[c]	4.5 ± 0.7[c,d]	9.8 ± 2.8	10.5 ± 3.0[d]	10.3 ± 2.7	11.3 ± 3.3[c,d]
15°	3.5 ± 1.1	4.3 ± 0.8[c]	4.7 ± 1.0[c]	4.6 ± 1.1[c]	13.4 ± 4.5	13.8 ± 4.8[d]	13.7 ± 4.5	15.0 ± 5.1[c,d]
30°	3.3 ± 0.8	4.4 ± 0.9[c]	4.8 ± 0.8[c]	4.5 ± 1.2[c]	15.7 ± 5.1	16.0 ± 5.1[c,d]	15.5 ± 4.9[e]	17.8 ± 5.4[c,d,e]
45°	3.2 ± 1.0	4.1 ± 0.8[c]	4.7 ± 0.9[c]	4.4 ± 1.5[c]	16.0 ± 5.4	16.4 ± 5.4[c,d]	15.9 ± 4.6[e]	18.5 ± 5.4[c,d,e]
60°	3.0 ± 1.2	4.0 ± 1.1[c]	4.4 ± 1.1[c]	4.3 ± 1.8[c]	15.4 ± 4.9	15.8 ± 4.8[d]	15.4 ± 4.1	18.0 ± 4.6[c,d]
75°	2.7 ± 1.1	3.8 ± 1.4[c]	3.8 ± 1.2[c]	4.0 ± 2.0[c]	14.2 ± 4.5	14.7 ± 4.4[d]	13.7 ± 3.9	16.8 ± 4.0[c,d]
90°	2.5 ± 1.0	3.4 ± 1.5	3.4 ± 1.3	3.7 ± 1.9	14.0 ± 4.4	14.3 ± 4.3[d]	12.7 ± 4.7	16.2 ± 3.8[c,d]
105°	2.4 ± 0.9	3.2 ± 1.3	3.1 ± 1.1	3.4 ± 1.6	14.5 ± 4.9	14.9 ± 4.6[d]	12.7 ± 5.7[e]	16.5 ± 4.0[c,d,e]
120°	2.5 ± 1.0	3.3 ± 1.3	3.2 ± 1.0[c]	3.4 ± 1.3	15.2 ± 5.8	15.6 ± 5.4[d]	13.3 ± 6.5[e]	17.4 ± 4.9[c,d,e]

[a]Values are reported as mean ± SD. ACLR, anterior cruciate ligament reconstruction; ALL, anterolateral ligament; ALLR, ALL reconstruction.
[b]Raw values, unadjusted for flexion angle.
[c]Significant difference from intact ($P < .05$ via a paired t test with Holm adjustment).
[d]Significant difference between ALL intact + ACLR and ALL deficient + ACLR ($P < .05$ via a paired t test with Holm adjustment).
[e]Significant difference between ALLR + ACLR and ALL deficient + ACLR ($P < .05$ via a paired t test with Holm adjustment).

with 80% power. To assess the 4 knee conditions (intact, ACLR with intact ALL, ACLR with ALLR, and ACLR with deficient ALL), all pairwise comparisons were made with paired t tests separately at each flexion angle. The Holm method was used to control the familywise error rate for the tests conducted within each flexion angle. Additionally, multifactorial models were built with data from all flexion angles to characterize the translation and rotation measurements more generally and to detect small but consistent differences between the conditions. Flexible linear mixed-effects models were built that incorporated a random intercept for each specimen and allowed a continuous cubic relationship for the flexion angle. Model selection was performed via the Akaike information criterion, and a compound symmetry correlation structure among conditions was fit. Residual diagnostics were performed, and models were iterated when assumptions were not met. These models were reported when they added valuable information beyond what was provided by the pairwise t tests. The statistical computing software R (R Foundation for Statistical Computing with *lme4, ggplot2, rms, reshape*, and *effects* packages) was used for all statistical analyses.[47]

RESULTS

Knee kinematics results for the ACLR with ALL-intact, ACLR with ALLR, and ACLR with ALL-deficient conditions are summarized in Tables 1 and 2.

Axial Plane Translation During a Simulated Pivot Shift

When subjected to a simulated pivot shift, all conditions (ACLR combined with ALL-intact, ALLR, and ALL-deficient states) had increases in axial plane

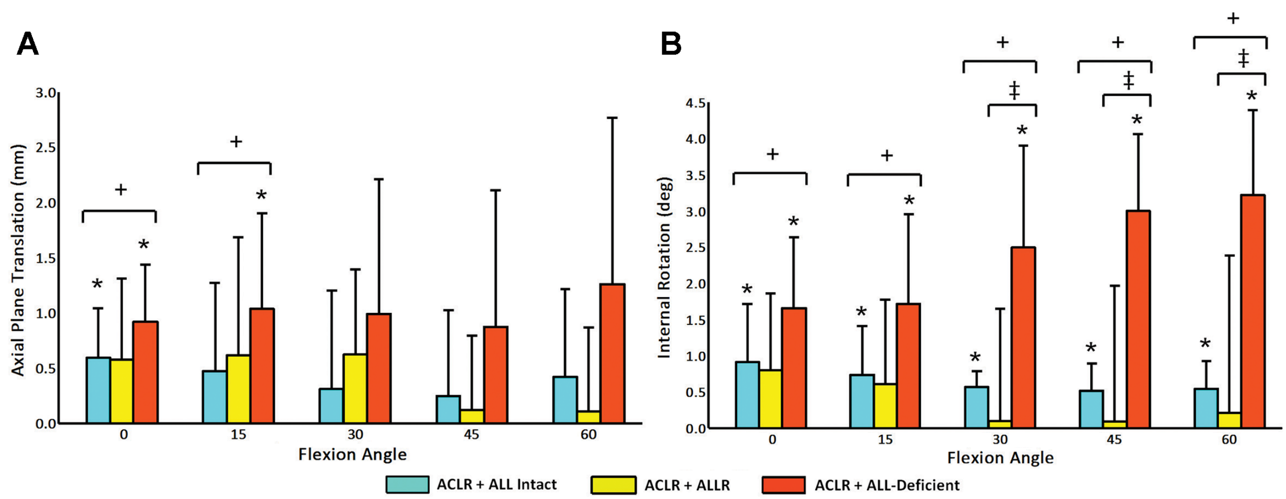

Figure 2. Change from intact state for (A) axial plane translation and (B) internal rotation in response to a simulated pivot shift (coupled 5-N·m internal rotation and 10-N·m valgus torques) for anterior cruciate ligament reconstruction (ACLR) with anterolateral ligament (ALL)–intact, ACLR with ALL reconstruction (ALLR), and ACLR with ALL-deficient states. Statistically significantly different *from intact, ⁺between ACLR + ALL-intact and ACLR + ALL-deficient, and ‡between ACLR + ALLR and ACLR + ALL-deficient ($P < .05$).

translation compared with the intact state throughout flexion; however, only for ACLR with an intact ALL at 0° (P = .012) and with a deficient ALL at 0° (P = .002) and 15° (P = .027) were the observed increases significant (Table 1 and Figure 2). When pooling evidence across flexion angles, the linear mixed-effects model demonstrated a significant increase in axial plane translation for the ACLR with ALL-deficient state compared with the intact state of 1.0 mm (95% CI, 0.6-1.5 mm; $P < .001$) and nonsignificant increases in translation of 0.4 mm for ACLR with an intact ALL (95% CI, 0.0-0.9 mm; P = .055) and 0.4 mm for ACLR with ALLR (95% CI, 0.0-0.9 mm; P = .055).

When combined with ACLR, the ALL-deficient state had significantly increased axial plane translation compared with an intact ALL at 0° (P = .012) and 15° (P = .030) of flexion. Pooling evidence across flexion angles, the linear mixed-effects model showed significant reductions in axial plane translation compared with the ALL-deficient state of 0.6 mm (95% CI, 0.2-1.1 mm; P = .002) when the ALL was intact and 0.6 mm (95% CI, 0.2-1.1 mm; P = .002) with ALLR.

Internal Rotation During a Simulated Pivot Shift

When subjected to a simulated pivot shift, the ACLR with ALL-deficient condition had significant increases in internal rotation compared with both the intact knee and ACLR with ALL-intact conditions for all flexion angles from 0° to 60° (Table 1 and Figure 2). When pooling evidence across flexion angles, the linear mixed-effects model demonstrated that the ACLR with ALL-deficient state had a significant increase of 2.4° (95% CI, 1.4°-3.4°; $P < .001$) of internal rotation compared with the intact knee and 1.8° (95% CI, 0.7°-2.8°; $P < .001$) of increased internal rotation compared with ACLR with an intact ALL.

When accompanied by ACLR, ALLR had significant reductions in internal rotation compared with ALL-deficient knees at 30° (P = .024), 45° (P = .010), and 60° (P = .014). Additionally, when pooling evidence across flexion angles, the linear mixed-effects model showed that ACLR with ALLR resulted in a significant reduction of 2.1° (95% CI, 1.0°-3.1°; $P <$ .001) of internal rotation compared with ACLR with a deficient ALL during a simulated pivot-shift test.

Internal Rotation During Internal Rotation Torque

The ACLR with ALL-deficient condition showed significant increases in internal rotation compared with the intact condition throughout flexion (Table 2 and Figure 3). Additionally, the ACLR with ALL-deficient state had a significant increase in internal rotation compared with ACLR with an intact ALL between 0° to 120° of flexion. For the ACLR with ALL-deficient state, modeled effects of 2.2° (95% CI, 1.1°-3.2°; $P < .001$) of increased internal rotation compared with the intact knee and 1.7° (95% CI, 0.7°-2.8°; $P < .001$) of increased internal rotation compared with ACLR with an intact ALL were observed when pooling evidence across flexion angles.

When accompanied by ACLR, ALLR had significant reductions in internal rotation compared with ALL-deficient knees at 30° (P = .0202), 45° (P = .00765), 105° (P = .042), and 120° (P = .0103). Additionally, when pooling evidence across flexion angles, the linear mixed-effects model demonstrated that ACLR with ALLR resulted in a significant reduction of 2.7° (95% CI, 1.7°-3.7°; $P <$ .001) of internal rotation compared with the ACLR with ALL-deficient state and a significant reduction of 1.0°

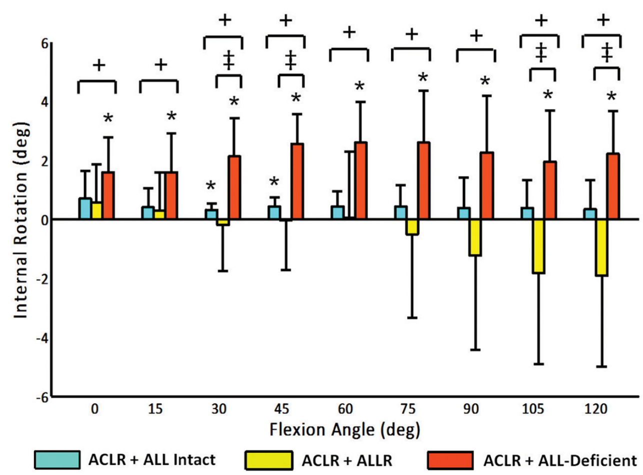

Figure 3. Internal tibial rotation in response to a 5-N·m internal rotation torque for anterior cruciate ligament reconstruction (ACLR) with anterolateral ligament (ALL)–intact, ACLR with ALL reconstruction (ALLR), and ACLR with ALL-deficient states compared with the intact state. Statistically significantly different *from intact, +between ACLR + ALL-intact and ACLR + ALL-deficient, and ‡between ACLR + ALLR and ACLR + ALL-deficient ($P < .05$).

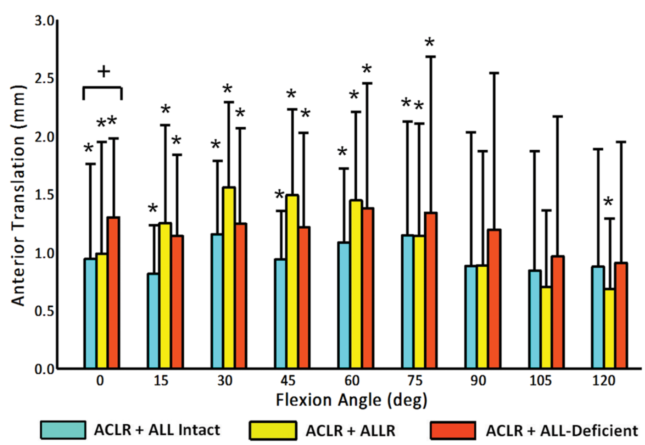

Figure 4. Anterior tibial translation in response to an 88-N anterior tibial load for anterior cruciate ligament reconstruction (ACLR) with anterolateral ligament (ALL)–intact, ACLR with ALL reconstruction (ALLR), and ACLR with ALL-deficient states compared with the intact state. Statistically significantly different *from intact and +between ACLR + ALL-intact and ACLR + ALL-deficient ($P < .05$).

(95% CI, 0.0°-2.0°; P = .0451) in internal rotation compared with ACLR with an intact ALL.

Anterior Tibial Translation During Anterior Tibial Load

Significant increases in anterior tibial translation (ATT) compared with the intact knee were observed for all tested states from 0° to 75° of flexion during an anterior tibial load (Table 2 and Figure 4). When pooling evidence across flexion angles, the linear mixed-effects model showed significant increases in ATT compared with the intact state of 1.0 mm (95% CI, 0.7-1.3 mm; $P < .001$), 1.1 mm (95% CI, 0.8-1.4 mm; $P < .001$), and 1.2 mm (95% CI, 0.9-1.5 mm; $P < .001$) for the ACLR with ALL-intact, ACLR with ALLR, and ACLR with ALL-deficient states, respectively. No significant differences in ATT were observed between the ALL conditions (intact ALL, ALLR, deficient ALL) combined with ACLR, except for at 0° (P = .0397) of flexion in which ACLR with a deficient ALL was significantly increased compared with ACLR with an intact ALL.

The largest ATT increase was observed at midflexion angles between 30° and 60° for all reconstruction conditions. At 30° and 90° of flexion, at which the Lachman and anterior drawer tests are respectively performed, increases in ATT compared with the intact state of 1.2 ± 0.6 mm (P = .001) and 0.9 ± 1.1 mm (P = .15) for ACLR with an intact ALL, 1.6 ± 0.7 mm ($P < .001$) and 0.9 ± 1.0 mm (P = .12) for ACLR with ALLR, and 1.2 ± 0.8 mm (P = .004) and 1.2 ± 1.3 mm (P = .12) for ACLR with a deficient ALL were observed.

DISCUSSION

The most important finding of this study was that combined anatomic ACLR and ALLR further reduced rotatory laxity compared with isolated ACLR in knees with a combined ACL and ALL deficiency. Isolated ACLR in an ALL-deficient knee resulted in significant residual internal rotation compared with the fully intact knee during applied internal rotation torques (0°-120° of knee flexion) and a simulated pivot shift (0°-60°). Moreover, models demonstrated that a deficient ALL contributed to 1.7° and 1.8° increases in internal rotation laxity during internal rotation and a pivot shift, respectively, compared with an intact ALL during ACLR. However, by combining ACLR with ALLR, internal rotation was significantly reduced and no longer significantly different from the intact state or ACLR with intact ALL state.

Recent biomechanical studies have reported that the ALL has a role in controlling rotational stability.[5,7,8,20,27,38,40,43,56] In part 1,[48] we biomechanically demonstrated that in the presence of a combined ACL and ALL lesion, there was significant internal rotatory instability and axial plane translation during the pivot-shift test compared with an isolated ACL tear. Parsons et al,[43] also in a biomechanical study, randomly analyzed the contribution of each individual ligament (ACL, FCL, ALL) and reported that the ALL was an important stabilizer for internal rotation at flexion angles greater than 35°. Furthermore, grade 3+ injuries during a pivot-shift test have been reported to materialize only once the ALL has been sectioned in ACL-deficient knees.[38] These studies have demonstrated the ALL's role in providing rotatory stability. Therefore, we postulated that the next step was to investigate anatomic ALLR.

This study demonstrated the capability of ALLR to further reduce knee laxity when combined with ACLR.

Monaco et al,[40] using an in vivo dynamic evaluation with navigation, similarly found that extra-articular reconstruction improved axial tibial rotation and stability during the pivot-shift test. During a simulated pivot-shift test, a significant reduction in internal rotation at 30°, 45°, and 60° of knee flexion was observed for the ACLR with ALLR state compared with the ACLR with ALL-deficient state. This suggests that extra-articular surgical treatment may be an appropriate consideration for patients with a residual positive pivot shift after isolated ACLR. Furthermore, ACLR with ALLR reduced internal rotation compared with the ACLR with ALL-deficient state. However, in some knee flexion angles (30°, 45°, 75°-120°), this resulted in nonsignificant, likely because of sample size, overconstraint of internal rotation. Thus, ALLR that aims to match the biomechanics of the native intact ALL may lead to better overall knee joint rotatory kinematics than ACLR alone.

As expected, ACLR with ALLR had a minimal effect on reducing ATT. At nearly all flexion angles (0°-75° and 120°), significant increases remained after ACLR with ALLR compared with the intact state. Furthermore, the differences between the 3 ALL conditions were small and nonsignificant throughout flexion (except at 0° between the intact and deficient ALL states). These findings corroborate basic ALL biomechanical studies and clinical findings that suggest that the ALL plays a smaller role in restricting ATT.[43,48] Thus, the added benefit of ALLR resides predominantly in serving as a complement to ACLR by limiting rotational laxity.

The anatomic ALLR presented in this study was based on recent detailed quantitative anatomic descriptions of the ALL.[27] Tunnel positions for ALLR were placed according to previously reported anatomic findings for the ALL's tibial and femoral attachment sites. A semitendinosus graft was chosen for reconstruction because it was believed to be strong enough to withstand rigorous robotic testing. Anatomic reconstructions and repairs have been validated biomechanically for other knee ligaments and have led to improved patient outcomes.[31] Anatomic reconstruction was chosen to prevent additional technique variables from confounding the kinematic results. We encourage future studies to investigate different anatomic and nonanatomic ALLR variations alike to identify the procedure that best replicates native knee biomechanics.

Previous lateral knee extra-articular techniques attempted to address residual rotational laxity by reconstructing the lateral knee structures in addition to intra-articular ACLR.[2,10,34,35,39,60,61] Marcacci et al[35] described combined intra-articular and extra-articular ACLR using hamstring tendons. The intra-articular portion consisted of intra-articular double-stranded ACLR with an "over-the-top" passage and soft tissue fixation with 2 staples slightly posterior to the lateral epicondyle. Extra-articular plasty was performed with the remaining part of the tendon passed beneath the iliotibial band but superficial to the FCL and fixed distal to the Gerdy tubercle. Marcacci et al[34] reported high satisfactory results from their technique. In a prospective clinical and radiographic evaluation study with a 10- to 13-year follow-up, they demonstrated that a combination of single-bundle ACLR plus extra-articular augmentation was capable of maintaining stability without an increased rate of degenerative arthritis, with more than 90% of knees normal or nearly normal as measured using the IKDC rating system.

Sonnery-Cottet et al[51] proposed a concurrent ACLR and ALLR technique. In their study, the ACL was reconstructed using a triple-stranded semitendinosus and single-stranded gracilis, and concurrent double-bundle ALLR was performed using the proximal free end of the gracilis. After defining the isometric point for the ALL on the lateral aspect of the distal femur, the gracilis extension of the ACL graft was passed distally through 2 tunnels drilled on the anterolateral aspect of the proximal tibia via access from 2 incisions (the lower/distal one just above the superolateral corner of the Gerdy tubercle and the second one above and lateral to this point) to replicate the triangular shape of the native ALL. Notably, however, this triangular shape was not described in a more recent quantitative anatomic study of the ALL on which the current study was based.[27]

Residual laxity after combined ACLR with ALLR, or in some cases overconstraint, may be attributed to the surgical reconstruction technique. We recommend future investigation into finding a surgical graft construct with stiffness matching the native ALL, identifying the ideal fixation angle for ALLR, examining the fixation order for ALLR and ACLR grafts when concurrently reconstructed, and determining the most appropriate traction tension that should be applied during ALLR graft fixation. We theorize that investigation into these variables may help to further refine the combined ACLR and ALLR procedures to match native knee biomechanics before widespread use. Furthermore, it is not known how often ALLR should be recommended to patients presenting with an ALL injury. The precise clinical indications for this type of reconstruction are still unclear. Sonnery-Cottet et al,[51] based on their experience, reported their indications for concurrent ACLR and ALLR to include patients presenting with a grade 2 or 3 pivot shift, an associated Segond fracture, a chronic ACL lesion, a high level of sporting activity, participation in pivoting sports, and/or a lateral femoral notch sign on radiographs.[21] Additionally, Ferretti et al[13,14] argued that peripheral plasty was indicated for patients with severe rotational instability during the pivot-shift maneuver, women, high-level athletes, and revision cases. However, further clinical outcome research is needed to determine the best indications for concurrent ACLR and ALLR.

We acknowledge some limitations to this study. Inherent to a time-zero cadaveric study, the results of this study do not reflect biological healing or graft incorporation effects on reconstruction graft performance. The use of allografts enabled better control over size, shape, and tissue quality for this biomechanical study. Our choice for using a semitendinosus allograft in ALLR was based on a comparison between the mean maximum load of this graft (1216 N), as reported by Noyes et al,[41] and that of the native ALL (175 N), as reported by Kennedy et al.[27] Furthermore, most surgeons are familiar in handling this tendon whether as an autograft or allograft. For in vivo conditions, we advocate for the use of autografts as groups have reported increased retear rates after allograft use compared with autografts in younger populations.[23] Therefore, this study does not provide specific recommendations regarding the clinical or surgical indications for ALLR. Also, this study did not examine other potential lateral knee restraints during pivot shift or internal rotation, such as the iliotibial band. However, this study did not violate those attachments at the knee and investigated the isolated function of the ALL during ACLR. Furthermore, clinical examinations and diagnostic imaging need to be further investigated to refine the diagnostic criteria for acute and chronic grade 3 ALL injuries.

CONCLUSION

This study found that combined anatomic ACLR and ALLR improved the rotatory stability of the knee compared with isolated ACLR in the setting of a concurrent ALL deficiency, as could be observed by an overall reduction of 2.1° in internal rotation during pivot shift and 2.7° during internal rotation torque between both conditions. Thus, for cases of a combined ACL and ALL deficiency with increased internal rotation laxity, reconstruction of both structures should be considered to better restore knee stability. The reduction in internal rotation observed when comparing the combined anatomic technique with the intact state, although not significant, raises a concern regarding the possibility of overconstraint.

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