The Role of the Peripheral Passive Rotation Stabilizers of the Knee With Intact Collateral and Cruciate Ligaments

A Biomechanical Study

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Background: A subset of patients have clinical internal and/or external knee rotational instability despite no apparent injury to the cruciate or collateral ligaments.

Purpose/Hypothesis: The purpose of this study was to assess the effect of sequentially cutting the posterolateral, anterolateral, posteromedial, and anteromedial structures of the knee on rotational stability in the setting of intact cruciate and collateral ligaments. It was hypothesized that cutting of the iliotibial band (ITB), anterolateral ligament and lateral capsule (ALL/LC), posterior oblique ligament (POL), and posteromedial capsule (PMC) would significantly increase internal rotation, while sectioning of the anteromedial capsule (AMC) and the popliteus tendon and popliteofibular ligament (PLT/PFL) would lead to a significant increase in external knee rotation.

Study Design: Controlled laboratory study.

Methods: Ten pairs (N = 20) of cadaveric knees were assigned to 2 sequential cutting groups (group 1: posterolateral-to-posteromedial [PL → PM] and group 2: posteromedial-to-posterolateral [PM → PL]). Specimens were subjected to applied 5-N/m internal and external rotation torques at knee flexion angles of 0°, 30°, 60°, and 90° while intact and after each cut state. Rotational changes were measured and compared with the intact and previous cut states.

Results: Sectioning of the ITB significantly increased internal rotation at 60° and 90° by 5.4° and 6.2° in group 1 (PL → PM) and 3.5° and 3.8° in group 2 (PM → PL). PLT/PFL complex sectioning significantly increased external rotation at 60° and 90° by 2.7° and 2.9° in group 1 (PL → PM). At 60° and 90° in group 2 (PM → PL), ALL/LC sectioning produced significant increases in internal rotation of 3.1° and 3.5°, respectively. In group 2 (PM → PL), POL sectioning produced a significant increase in internal rotation of 2.0° at 0°. AMC sectioning significantly increased external rotation at 30° to 90° of flexion with a magnitude of change of <1° in both groups 1 (PL → PM) and 2 (PM → PL).

Conclusion: Collectively, the anterolateral corner structures provided primary internal rotation control of the knee from 60° to 90° of knee flexion in knees with intact cruciate and collateral ligaments. The ITB was the most significant primary stabilizer of internal rotation. The POL had a primary role for internal rotational stability at full extension. The PLT/PFL complex was a primary stabilizer for external rotation of the knee at 60° and 90°.

Clinical Relevance: This study delineates the primary and secondary roles of the ITB, ALL/LC, POL, and PLT/PFL to rotatory stability of the knee and provides new information to understand knee rotational instabilities.

Keywords: rotational instability; anterolateral ligament; iliotibial band; popliteus tendon; popliteofibular ligament; posterior oblique ligament; knee ligaments

Original Research

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Rotational instability of the knee in the presence of intact cruciate and collateral ligaments is a complex clinical problem to accurately diagnose and treat. Although advances in anatomic and biomechanical understanding of the knee have led to improved treatment of ligament injuries, there...
is still a subset of patients who present with symptoms of rotational instability despite no obvious structural injury on physical examination or magnetic resonance imaging (MRI). Furthermore, some of the patients with intact cruciate and collateral ligaments may have sustained injuries to other structures that heal elongated, resulting in subtle laxity that can be difficult to detect on clinical examination. In the chronic phase, these structures may have a normal appearance on MRI. Patients may complain of rotational instability with limitations during athletic activity, especially during pivoting and lateral movements. The role of the cruciate and collateral ligaments in controlling knee rotation has been studied in detail.\textsuperscript{10,17,20,21,47,48} However, the role of other knee structures in controlling internal and external rotation of the knee in the face of these intact primary ligamentous stabilizers has not been well described.

Currently, there remains a lack of consensus on whether other ligament or capsular structures provide primary or secondary restraints to rotational laxity when the cruciate and collateral ligaments are intact. Delineation of these structures and their respective function will be a key component to the understanding of rotational instability in those patients and potentially in those with residual rotational instability after “anatomic” ligament reconstructions.\textsuperscript{2,4,14,23,24,41} Therefore, the purpose of this study was to assess which anatomic structures have primary and secondary stabilization roles for knee internal and external rotation in the setting of intact cruciate and collateral ligaments. The effect of sequentially cutting the posterolateral, anterolateral, posteromedial, and anteromedial structures of the knee on rotational stability in the setting of intact cruciate and collateral ligaments was assessed in a biomechanical setup. It was hypothesized that sectioning of the iliotibial band (ITB), anterolateral ligament and lateral capsule (ALL/LC), posterior oblique ligament (POL), and the posteromedial capsule (PMC) would significantly increase internal rotation, while sectioning the anteromedial capsule (AMC) and the popliteus tendon and popliteofibular ligament (PLT/PFL) would lead to a significant increase in external knee rotation.

**METHODS**

**Specimen Preparation**

Ten pairs (N = 20) of fresh-frozen, male cadaveric knee specimens (mean age, 57.8 years; range, 47-63 years) with no history of prior injury, surgery, anatomic abnormality, ligament instability, or osteoarthritis were included in this study. Institutional review board approval was not required because deidentified cadaveric specimens are exempt from review at our institution. The cadaveric specimens utilized in this study were donated to a tissue bank for the purpose of medical research and then purchased by our institution. All specimens were stored at \(-20°C\) and thawed at room temperature 24 hours prior to preparation. Once testing was completed, each specimen underwent diagnostic arthroscopy to confirm the absence of intra-articular pathology.

In preparation for potting, the tibial, fibular, and femoral diaphyses were cut 20 cm from the joint line. Sharp dissection to bone was performed, and all soft tissues were removed 10 cm distal and proximal to the joint line and the fibula was fixed to the tibia in its anatomic position. The tibia, fibula, and femur were potted in a cylindrical mold filled with poly methyl methacrylate (PMMA) (Fricke Dental International Inc). The skin and subcutaneous tissues were removed and all relevant structures were identified before the specimen was mounted in the robotic testing system. The knee was covered in gauze and kept moist with 0.9% saline at all times throughout preparation, setup, and biomechanical testing. During specimen preparation for each knee, range of motion (flexion-extension and internal-external rotation) was actively tested to detect and reduce the potential effect of joint stiffness and rigidity.

**Robotic Testing Setup**

Each knee was held in an inverted orientation, with the potted distal end secured in a custom-made fixture mounted onto a universal force/torque sensor (Delta F/T Transducer, ATI Industrial Automation) attached to the end effector of a 6-degrees-of-freedom robotic arm (Kuka KR-60-3, Kuka Robotics). The potted femur was then rigidly fixed onto a stationary pedestal (Figure 1).

Next, the stylus tip of a portable measuring arm (Romer Absolute Arm, Hexagon Metrology; manufacturer-reported point repeatability of 0.025 mm) was used to define the knee joint coordinate system by collecting points at the medial- and lateral-most aspects of the tibial plateau, the medial and lateral femoral epicondyles, and along the tibial diaphysis.\textsuperscript{1,2,52} The coordinate system defined the knee joint center of rotation and the anterior-posterior, medial-lateral, and superior-inferior axes. Prior to testing,

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Ethical approval for this study was waived by the Steadman Philippon Research Institute.
Figure 1. The robotic setup with the inverted right knee mounted in the robotic testing system. Tag stitches were placed to identify the structures to be sectioned before the knee was mounted. The skin and subcutaneous tissue were removed so that the structures could be easily identified, and the knee was covered in gauze and kept moist with 0.9% saline at all times throughout preparation, setup, and biomechanical testing.

The knee was robotically subjected to a full passive path motion (0° to 120° of flexion) with minimal forces and torques on all axes. The native passive path of the knee in neutral rotation was recorded from full extension to 120° in 1° increments with minimized forces (<5 N) and torques (<0.5 N·m) in the remaining 5 degrees of freedom. A 1-N compressive load was applied along the axis of the tibial shaft to ensure tibiofemoral contact throughout testing. This robotic testing setup has been previously described and validated for knee joint kinematic testing.8,9

Biomechanical Testing

Based on previous anatomic studies and pilot tests, 6 key structures (3 medial and 3 lateral) were investigated by sequential cutting in the setting of intact cruciate and collateral ligaments.32,42,45,47,51 The medial structures sectioned were the PMC, the POL, and the AMC. The lateral structures sectioned were the PLT/PFL, the ALL/LC (mid-third lateral capsular ligament) and the ITB. During pilot testing, sectioning of the oblique posterior ligament, the lateral posterior capsule, and the medial posterior capsule did not produce observable increases in rotation. These structures were therefore not included in the final sectioning study.

The first knee of each matched pair was randomly assigned to 1 of 2 cutting sequences, and the contralateral knee was assigned to the alternate sequence. The cutting sequence for group 1 was from posterolateral-to-posteromedial (PL→PM): (1) PLT/PFL, (2) ALL/LC, (3) ITB, (4) AMC, (5) POL, and (6) PMC. The cutting sequence for group 2 was from posteromedial-to-posterolateral (PM→PL): (1) PMC, (2) POL, (3) AMC, (4) ITB, (5) ALL/LC, and (6) PLT/PFL (Table 1).

Robotic simulated clinical examinations were performed according to previously reported protocols to assess for rotatory laxity.8 During pilot testing, a 10-N axial compressive load was initially used. This was found to be an excessive axial load affecting the magnitude of observed rotational changes with ligament sectioning and was therefore reduced to 1 N, which replicated the clinical setting of evaluating rotation with near-zero axial loads. Internal and external rotation torques of 5 N·m were performed at 0° (full extension), 30°, 60°, and 90° of knee flexion for the intact state and after each cut state. Prior to each testing state, the order of flexion angles was randomized to decrease the potential effects of repetitive testing. Data from the internal and external rotation torques applied during biomechanical testing were recorded as degrees of rotation about the axis of the tibial shaft from the center of the knee joint, defined by the 3-dimensional coordinate system.

Popliteus Tendon and Popliteofibular Ligament Sectioning

The PLT was identified and sectioned in the popliteal sulcus with the knee positioned at 90° of flexion through a 2-cm incision along the fibers of the ITB and a 2-cm vertical incision in the capsule.22 The PFL was identified with the knee in 30° of flexion and was cut at its attachment to the musculotendinous junction of the popliteus muscle.
Anterolateral Ligament and Lateral Capsule (Mid-third Lateral Capsular Ligament) Sectioning

With the knee flexed to 90°, the ALL/LC tibial attachment was identified midway between the center of Gerdy’s tubercle and the anterior margin of the fibular head, 9.5 mm distal to the joint line, as described by both Kennedy et al. and Terry and LaPrade. The ALL/LC was released from the anterior margin of the fibular collateral ligament (FCL) extending 7 cm anteromedial to the center of the ALL tibial attachment. The ALL/LC was released as one unit. Careful attention was made to ensure that no injury to the lateral meniscus occurred.

Iliotibial Band Sectioning

The borders of the ITB were identified with the knee positioned at 90° of flexion. The capsulo-osseous and superficial fibers of the ITB were sectioned off the surrounding area of Gerdy’s tubercle, 5 mm anteromedial from the center of the ALL and extending to the lateral border of the patellar tendon (Figure 3). Using dissection scissors, the ITB was released from the underlying capsule to the level of the joint line.

Anteromedial Capsule Tibial Attachment Sectioning

The AMC was identified at 90° of knee flexion and located between the medial border of the patellar tendon and the anterior margin of the superficial medial collateral ligament (sMCL). It was released from the tibia 15 mm distal to the joint line with an average cut length of 22.7 mm. The tibial attachment sites of the medial meniscus and anterior medial meniscus root were not disrupted. The deep medial collateral ligament (dMCL) was also left intact (Figure 4).

Posterior Oblique Ligament Sectioning

With the knee positioned at 30° of flexion, the central arm of the POL was identified adjacent to the posterior fibers of the superficial MCL, according to LaPrade et al. The POL, including the superficial POL, was sectioned 1 cm distal to its femoral attachment.
Peripheral Rotational Stabilizers of the Knee

RESULTS

All numerical data for group 1 (PL → PM) and group 2 (PM → PL) are presented in Tables 2 and 3, respectively. More detailed results and a comprehensive reporting of statistical analyses can be found in the Appendix.

Validation Analysis

For the intact and fully sectioned states, the same knee condition existed regardless of cutting order, and thus equitable comparisons could be made between paired specimens. There was no significant difference (P > .25 in all cases) in internal or external rotation between paired knee specimens randomized into group 1 (PL → PM) or group 2 (PM → PL) at all flexion angles for the intact state and the fully sectioned state. Differences observed between the paired knees can therefore be attributed to the sectioning sequence and are not due to variability between the paired knees.

Internal Rotation

Iliotibial Band. In group 1 (PL → PM), release of the ITB after sectioning of the PLT/PFL and the ALL/LC complexes caused an increase in internal rotation of 5.4° at 60° (95% CI, 3.1°–7.6°, P = .002) and 6.2° at 90° (95% CI, 3.8°–8.6°, P = .001) (Table 2, Figure 5). In group 2 (PM → PL), release of the ITB after sectioning of the medial structures (PMC, POL, and AMC) resulted in a significant increase in internal rotation of 3.5° at 60° (95% CI, 1.5°–5.4°, P = .01) and 3.8° at 90° (95% CI, 2.1°–5.6°, P = .003) (Table 3, Figure 6). During sequential cutting in group 1 and group 2, sectioning of the ITB produced significant changes in internal rotation (P < .05) at 0° and 30°; however, the magnitude of change was <1° (Tables 2 and 3, Figures 5 and 6).

Anterolateral Ligament and Lateral Capsule (Mid-third Lateral Capsular Ligament). Sectioning of the ALL/LC in group 2 resulted in significant changes in internal rotation of <2.5° at 90° of knee flexion (95% CI, 0.5°–4.7°, P = .01) and 3.5° at 90° (95% CI, 2.0°–5.1°, P = .003). At 0° and 30°, cutting of the ALL/LC resulted in significant changes of <1.5° of internal rotation (P < .05) (Table 3, Figure 6). Sectioning of the ALL/LC in group 1 produced significant (P < .05) increases of <0.5° of internal rotation throughout flexion angles from 0° to 90° (Table 2, Figure 5).

Posterior Oblique Ligament. Sectioning of the POL in group 2 produced a significant increase in internal rotation of 2.0° at 0° of knee flexion (95% CI, 1.5°–2.5°, P < .001). Significant (P < .05) changes of ≤1° were observed at flexion angles 30° through 90° (Table 3, Figure 6). Sectioning of the POL in group 1 produced significant (P < .05) internal rotation increases of <2° at 0° and 30° of flexion (Table 2, Figure 5).

PosteroMedial Capsule. In group 1, sectioning of the PMC resulted in significant (P < .05) increases of <0.7° in internal rotation at 0°, 30°, and 60° (Table 2, Figure 5). In
PLT/PFL 12.1 ± PMC 11.3 ± PFL, popliteus tendon and popliteofibular ligament; PMC, posteromedial capsule; POL, posterior oblique ligament.

*Significantly different compared with previous cut state.

Changes in internal rotation from the intact state during a 5-N m internal rotation torque when sequentially cutting structures in group 1 (PL → PM). ALL/LC, anterolateral ligament and capsule; ITB, iliotibial band; AMC, anteromedial capsule; PM, posterolateral-to-posteromedial; PLT/PFL, popliteus tendon and popliteofibular ligament; PMC, posteromedial capsule; POL, posterior oblique ligament.

**TABLE 2**
Posterolateral-to-Posteromedial (Group 1) Sequential Sectioning: Responses to 5-N m Internal and External Rotation Torques at Various Flexion Angles

| Testing State | Internal Rotation, deg | External Rotation, deg |
|---------------|------------------------|------------------------|
|               | 0°  | 30°  | 60°  | 90°  | 0°  | 30°  | 60°  | 90°  |
| Intact        | 8.5 ± 2.5 | 17.5 ± 4.5 | 18.0 ± 5.0 | 16.6 ± 3.6 | 12.7 ± 2.7 | 17.7 ± 4.6 | 16.8 ± 4.5 | 18.0 ± 3.4 |
| PLT/PFL       | 8.6 ± 2.5 | 17.6 ± 4.7 | 18.5 ± 5.0 | 17.1 ± 3.8 | 13.1 ± 2.8 | 18.7 ± 4.5 | 19.5 ± 4.1 | 20.9 ± 3.8 |
| ALL/LC        | 8.8 ± 2.6 | 18.1 ± 4.9 | 18.9 ± 5.1 | 17.6 ± 3.8 | 13.2 ± 2.8 | 18.9 ± 4.5 | 19.7 ± 4.1 | 21.2 ± 4.1 |
| ITB           | 8.9 ± 2.7 | 19.4 ± 5.0 | 24.3 ± 4.9 | 23.8 ± 3.6 | 13.3 ± 2.8 | 19.0 ± 4.5 | 19.9 ± 4.2 | 21.4 ± 4.0 |
| AMC           | 8.9 ± 2.7 | 19.6 ± 5.1 | 24.4 ± 5.0 | 24.3 ± 3.7 | 13.4 ± 2.8 | 19.3 ± 4.4 | 20.3 ± 4.1 | 22.1 ± 3.9 |
| POL           | 10.8 ± 2.4 | 21.2 ± 4.7 | 25.2 ± 5.1 | 24.6 ± 3.9 | 13.6 ± 2.8 | 19.3 ± 4.4 | 20.4 ± 4.1 | 22.2 ± 3.9 |
| PMC           | 11.3 ± 2.5 | 21.3 ± 4.7 | 25.3 ± 5.1 | 24.7 ± 4.0 | 13.7 ± 2.9 | 19.4 ± 4.4 | 20.5 ± 4.1 | 22.3 ± 3.9 |

All data are presented as mean ± SD. ALL/LC, anterolateral ligament and capsule; AMC, anteromedial capsule; ITB, iliotibial band; PLT/PFL, popliteus tendon and popliteofibular ligament; PMC, posteromedial capsule; POL, posterior oblique ligament.

**TABLE 3**
Posteromedial-to-Posterolateral (Group 2) Sequential Sectioning: Responses to 5-N m Internal and External Rotation Torques at Various Flexion Angles

| Testing State | Internal Rotation, deg | External Rotation, deg |
|---------------|------------------------|------------------------|
|               | 0°  | 30°  | 60°  | 90°  | 0°  | 30°  | 60°  | 90°  |
| Intact        | 9.1 ± 2.0 | 17.8 ± 4.5 | 18.1 ± 4.9 | 16.4 ± 2.8 | 12.7 ± 3.0 | 17.5 ± 5.3 | 17.5 ± 5.3 | 18.9 ± 3.9 |
| PMC           | 9.3 ± 2.3 | 17.9 ± 4.5 | 18.3 ± 4.9 | 16.6 ± 2.8 | 13.0 ± 3.1 | 17.6 ± 5.3 | 17.7 ± 5.2 | 19.2 ± 3.9 |
| POL           | 11.3 ± 2.4 | 18.9 ± 4.7 | 18.5 ± 5.0 | 16.7 ± 2.9 | 13.1 ± 3.1 | 17.8 ± 5.2 | 17.8 ± 5.2 | 19.3 ± 3.9 |
| AMC           | 11.4 ± 2.5 | 18.9 ± 4.7 | 18.6 ± 5.0 | 16.9 ± 2.9 | 13.3 ± 3.1 | 18.1 ± 5.4 | 18.2 ± 5.4 | 19.7 ± 4.1 |
| ITB           | 11.5 ± 2.5 | 20.0 ± 4.7 | 22.1 ± 5.4 | 20.7 ± 3.6 | 13.3 ± 3.2 | 18.3 ± 5.4 | 18.4 ± 5.4 | 19.8 ± 4.2 |
| ALL/LC        | 12.0 ± 2.9 | 21.4 ± 4.5 | 25.2 ± 5.0 | 24.3 ± 3.5 | 13.4 ± 3.1 | 18.3 ± 5.4 | 18.3 ± 5.4 | 19.9 ± 4.1 |
| PLT/PFL       | 12.1 ± 2.9 | 21.6 ± 4.5 | 25.3 ± 5.1 | 24.5 ± 3.5 | 13.6 ± 3.2 | 19.2 ± 5.6 | 20.5 ± 5.5 | 22.6 ± 4.3 |

All data are presented as mean ± SD. ALL/LC, anterolateral ligament and capsule; AMC, anteromedial capsule; ITB, iliotibial band; PLT/PFL, popliteus tendon and popliteofibular ligament; PMC, posteromedial capsule; POL, posterior oblique ligament.

Figure 5. Changes in internal rotation from the intact state during a 5-N m internal rotation torque when sequentially cutting structures in group 1 (PL → PM). ALL/LC, anterolateral ligament and capsule; ITB, iliotibial band; AMC, anteromedial capsule; PL → PM, posterolateral-to-posteromedial; PLT/PFL, popliteus tendon and popliteofibular ligament; PMC, posteromedial capsule; POL, posterior oblique ligament. *Significantly different compared with previous cut state (P < .05).

Figure 6. Changes in internal rotation from the intact state during a 5-N m internal rotation torque when sequentially cutting structures in group 2 (PM → PL). ALL/LC, anterolateral ligament and capsule; AMC, anteromedial capsule; ITB, iliotibial band; PLT/PFL, popliteus tendon and popliteofibular ligament; PM → PL, posteromedial-to-posterolateral; PMC, posteromedial capsule; POL, posterior oblique ligament. *Significantly different compared with previous cut state (P < .05).
group 2, sectioning of the PMC produced significant ($P < .05$) increases in internal rotation of $<0.3^\circ$ at $30^\circ$, $60^\circ$, and $90^\circ$ of knee flexion (Table 3, Figure 6).

**Anteromedial Capsule.** In group 2, significant ($P < .05$) changes of $<0.3^\circ$ of internal rotation were observed at flexion angles $0^\circ$ through $90^\circ$ when the AMC was sectioned (Table 3, Figure 6). In group 1, significant ($P < .05$) increases of $<0.5^\circ$ in internal rotation at $30^\circ$ and $90^\circ$ of knee flexion were observed when the AMC was sectioned (Table 2, Figure 5).

**Popliteus Tendon and Popliteofibular Ligament.** In both group 1 and group 2, sectioning of the PLT/PFL produced significant ($P < .05$) increases in internal rotation of $\leq 0.5^\circ$ throughout flexion angles $0^\circ$ to $90^\circ$ (Tables 2 and 3, Figures 5 and 6).

**External Rotation**

**Popliteus Tendon and Popliteofibular Ligament.** Sectioning of the PLT/PFL complex in group 1 (PL → PM) produced significant increases in external rotation of $2.7^\circ$ at $60^\circ$ (95% CI, 1.4°-4.0°, $P = .009$) and $2.9^\circ$ at $90^\circ$ (95% CI, 1.9°-3.9°, $P < .001$). At $0^\circ$ and $30^\circ$, significant ($P < .05$) changes of $<1^\circ$ were observed (Table 2, Figure 7). In group 2 (PM → PL), sectioning of the PLT/PFL complex increased external rotation significantly by $2.2^\circ$ at $60^\circ$ (95% CI, 1.5°-3.0°, $P < .001$) and $2.7^\circ$ at $90^\circ$ (95% CI, 1.8°-3.6°, $P < .001$). Significant increases of $<1^\circ$ occurred at $0^\circ$ and $30^\circ$ (Table 3, Figure 8).

**Anteromedial Capsule.** In group 2, significant ($P < .05$) increases of $<0.5^\circ$ of external rotation were observed when the AMC was sectioned from flexion angles $0^\circ$ through $90^\circ$ (Table 3, Figure 8). Sectioning of the AMC in group 1 produced significant ($P < .05$) increases of $<0.5^\circ$ at $30^\circ$ and $60^\circ$ of knee flexion (Table 2, Figure 7).

**Posterior Oblique Ligament.** In group 2, sectioning of the ITB resulted in significant ($P < .05$) external rotation increases of $<0.3^\circ$ at $0^\circ$, $30^\circ$, and $90^\circ$ of knee flexion (Table 3, Figure 8). In group 1, sectioning of the ITB resulted in significant ($P < .05$) external rotation increases of $<0.3^\circ$ at $0^\circ$ and $60^\circ$ of knee flexion (Table 2, Figure 7).

**Iliotibial Band.** In group 2, sectioning of the ITB produced significant ($P < .05$) increases in external rotation of $<0.3^\circ$ at $0^\circ$, $30^\circ$, and $90^\circ$ of knee flexion (Table 3, Figure 8). In group 1, sectioning of the ITB resulted in significant ($P < .05$) external rotation increases of $<0.3^\circ$ at $0^\circ$ and $60^\circ$ of knee flexion (Table 2, Figure 7).

**Anterolateral Ligament and Lateral Capsular Ligament.** Sectioning of the ALL/LC complex produced significant ($P < .05$) increases in external rotation of $<0.3^\circ$ from $0^\circ$ through $90^\circ$ in group 2 (Table 3, Figure 8). In group 1, sectioning of the ALL/LC complex produced significant ($P < .05$) increases in external rotation of $<0.3^\circ$ at $0^\circ$ through $60^\circ$ of knee flexion (Table 2, Figure 7).

**DISCUSSION**

The most important finding of this study was that in the setting of intact cruciate and collateral ligaments, the ITB was a significant primary stabilizer for internal rotation of the knee at high flexion angles ($60^\circ$–$90^\circ$). The ALL/LC complex was found to have a significant role in controlling internal rotation at high flexion angles; however, it was less substantial than the ITB. With the knee in full extension ($0^\circ$), the POL was a primary stabilizer for internal rotation. In addition, the PLT/PFL complex was a significant primary stabilizer of external rotation of the tibia at high flexion angles ($60^\circ$–$90^\circ$). Furthermore, the posteromedial and...
antomedial capsules had small, yet significant, contributions to rotational stability.

Identifying rotational instability in a clinical setting can be challenging because subtle changes are often difficult to detect during physical examination. Although sometimes small, these increases in rotation can impair knee function and reduce patient quality of life. A recent study of in vivo 3-dimensional gait kinematics between anterior cruciate ligament (ACL)–deficient knees and ACL-intact knees reported a significant increase of $1.4^{\circ} \pm 0.2^{\circ}$ in internal rotation in the ACL deficient group. The ACL-deficient knee patients were noncopers and unable to return to their premorbid level of sports play or activity. An amplitude of greater than $2^{\circ}$ was therefore believed to be a clinically relevant amount of rotational instability in this study.

The magnitude of the increase in internal rotation after release of the ITB correlated with the intact versus cut state of the ALL/LC complex. Increased internal rotation was found for a combined release of the ITB and ALL/LC complex compared with an isolated ITB release. Sectioning of the ALL/LC produced an amplitude of $>2^{\circ}$ of internal rotation change only when the ITB had been previously sectioned. This intricate interaction between the ITB and the ALL/LC indicates a contribution of both structures for internal rotational control. However, the magnitude of rotational changes observed when sectioning the ALL/LC prior to the ITB (group 1 [PL → PM]) was $<2^{\circ}$, indicating the ALL/LC complex was a less important secondary stabilizer of internal rotation compared with the ITB.

The importance of the ITB in controlling internal rotation has been previously reported. Lutz et al reported that the “Kaplan fibers” (attachment of the ITB to the distal femur) acted as a stabilizing ligament, holding the distal portion of the ITB against the lateral epicondyle and increasing tension during internal rotation. Avulsions of the proximal attachment of the ITB have also been reported in patients suffering from increased anterolateral rotational instability of the knee.

An injury to the anterolateral corner (ALC) structures results in what has historically been referred to as anterolateral rotatory instability (ALRI). ALRI has been defined as a combined anterior translational and internal rotational movement of the tibia. According to some studies, the ALC structures are frequently injured during ACL tears. Wroble et al reported a significant increase in internal rotation at knee flexion angles of $30^{\circ}$ to $90^{\circ}$ after sectioning the entire ALC but made no distinction as to the individual contributions of each structure. Terry and LaPrade demonstrated a correlation between increased anterior translation with the knee at $25^{\circ}$ of flexion on the Lachman test and injury to the biceps–capsulo-osseous iliotibial tract confluence.

Traditionally, the ACL has been considered the main structure for internal rotatory stability of the knee at lower flexion angles. The results of this study demonstrate the significant role of the ITB in internal rotatory stability of ACL-intact knees. Furthermore, it outlines the interplay between the ALC structures (ALL/LC complex and the ITB) in limiting internal rotation of the knee.

The role of the ALL in rotational control of the knee is not without controversy. Studies by Rasmussen et al, Sonnery-Cottet et al, and Parsons et al have reported the ALL to have a significant role in controlling internal rotation with a deficient ACL. Nitri et al reported that in a combined ACL and ALL injury, the only means of restoring rotatory stability was to reconstruct both structures and not just the ACL in isolation. However, not all studies in the literature are in line with those findings. Kittl et al reported only a minor contribution of the ALL on internal rotation stability with a deficient ACL. In an anatomic and biomechanical study by Rahmemai-Azar et al, the anterolateral capsule was reported to be lacking any structural and biomechanical properties of a ligament, posing questions about the existence of the ALL as a distinct structure (vs solely a capsular thickening).

The role of the anterolateral structures in controlling internal rotation of the knee. In addition, lateral extra-articular tenodesis procedures have been reported to improve the pivot-shift grade in biomechanical and clinical studies, which supports the role of the anterolateral structures in controlling internal rotation of the tibia. The role of individual capsular structures in providing rotatory stability of the knee had not been investigated thoroughly prior to the present study.

The PLT/PFL was a primary stabilizer of the knee in external rotation at higher flexion angles ($60^{\circ}$–$90^{\circ}$). This has been reported previously and confirmed in this study. Sectioning of the AMC and PMC (Table 3) demonstrated significant changes in external rotation; however, the magnitudes of these changes were $<1^{\circ}$. The POL contributed significantly to restraining internal rotation of the tibia near full extension, confirming results reported in previous studies. The PMC did not contribute significantly to rotational stability in the present study. In contrast, Robinson et al reported a significant increase in internal rotation laxity at $0^{\circ}$ and $15^{\circ}$ after sectioning the PMC; however, the PMC in their study included what is termed the POL in the present study.

We acknowledge some limitations in this study. This was a cadaveric study with a relatively limited number of samples. The sequences of sectioning may overestimate each individual component’s stability because of the interplay between the structures that cannot be separated. As a cadaveric study, we were not able to assess the contribution and functional stability of muscles. Release of the AMC did not include complete release of the meniscotibial attachment to the medial meniscus anteriorly and subsequently might have limited the magnitude of change with its release. Furthermore, the magnitude of rotation that can cause symptoms and thus be clinically significant is still unclear. Currently there is limited literature on this subject, and using the 3-dimensional kinematics in the absence of axial compression forces might overestimate the effect of these injuries.
CONCLUSION

Collectively, the anterolateral corner structures had a primary role in internal rotational control of the knee from $60^\circ$ to $90^\circ$ of knee flexion in knees with intact cruciate and collateral ligaments. The ITB was the most significant primary stabilizer for internal rotation, while the ALL/LC complex had a significant secondary role. The POL had a primary role for internal rotational stability at full extension, while the PLT/PFL complex was a primary stabilizer for external rotation of the knee at higher flexion angles ($60^\circ$ and $90^\circ$).

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## APPENDIX

| Internal Rotation | Lateral-to-Medial Sequential Sectioning | Medial-to-Lateral Sequential Sectioning |
|-------------------|----------------------------------------|----------------------------------------|
| Flexion Angle     | Specific Comparison | Mean | 95% CI | Holm P-value | Specific Comparison | Mean | 95% CI | Holm P-value |
|                   | Comparison Type     | Diff | Lower | Upper | t           |               |               |               |
| 0                 | Comparisons to Intact |       |       |       |             |     |       |       |             |     |       |       |
|                   | PLT/PFL vs Intact   | 0.2  | 0.1   | 0.3  | 5.015      | 0.0065     | PMC vs Intact | 0.2  | 0.0   | 0.4  | 2.146 | 0.0925 |
|                   | ALL/LC vs Intact    | 0.3  | 0.2   | 0.4  | 4.779      | 0.0065     | POL vs Intact | 2.2  | 1.6   | 2.8  | 8.697 | <0.001 |
|                   | ITB vs Intact      | 0.4  | 0.2   | 0.6  | 4.975      | 0.0065     | AMC vs Intact | 2.3  | 1.7   | 2.9  | 8.610 | <0.001 |
|                   | AMC vs Intact      | 0.5  | 0.3   | 0.7  | 4.907      | 0.0065     | ITB vs Intact | 2.4  | 1.8   | 3.0  | 9.111 | <0.001 |
|                   | POL vs Intact      | 2.3  | 1.5   | 3.1  | 6.405      | 0.0014     | ALL/LC vs Intact | 2.9  | 2.1   | 3.7  | 8.251 | <0.001 |
|                   | PMC vs Intact      | 2.9  | 1.9   | 3.8  | 6.866      | 0.0014     | PLT/PFL vs Intact | 3.0  | 2.2   | 3.8  | 8.552 | <0.001 |
|                   |                      |       |       |       |             |               |               |               |
| 30                | Comparisons to Intact |       |       |       |             |     |       |       |             |     |       |       |
|                   | PLT/PFL vs ALL/LC   | 0.1  | 0.1   | 0.2  | 4.027      | 0.0119     | PMC vs Intact | 0.2  | 0.0   | 0.4  | 3.872 | <0.001 |
|                   | ALL/LC vs ITB      | 0.1  | 0.1   | 0.2  | 3.474      | 0.0140     | POL vs Intact | 0.1  | 0.0   | 0.2  | 3.474 | <0.001 |
|                   | ITB vs AMC         | 0.0  | 0.0   | 0.1  | 1.278      | <0.2331    | ALL/LC vs Intact | 0.7  | 0.3   | 1.0  | 3.524 | <0.001 |
|                   | AMC vs POL         | 1.8  | 0.9   | 2.7  | 4.466      | 0.0078     | POL vs PMC    | 0.5  | 0.3   | 0.8  | 4.939 | <0.001 |
|                   | POL vs PMC         | 0.6  | 0.2   | 0.9  | 3.841      | <0.019     |                      |       |       |       |       |       |
| 60                | Comparisons to Intact |       |       |       |             |     |       |       |             |     |       |       |
|                   | PLT/PFL vs ALL/LC   | 0.5  | 0.3   | 0.7  | 5.148      | 0.0036     | PMC vs Intact | 0.9  | 0.5   | 1.4  | 4.430 | 0.0082 |
|                   | ALL/LC vs ITB      | 1.3  | 0.5   | 2.1  | 3.524      | 0.0194     | POL vs Intact | 0.1  | 0.0   | 0.1  | 2.486 | 0.0366 |
|                   | ITB vs AMC         | 0.2  | 0.1   | 0.3  | 7.212      | <0.001     | ALL/LC vs Intact | 0.9  | 0.7   | 1.3  | 5.876 | <0.001 |
|                   | AMC vs POL         | 1.5  | 0.5   | 2.6  | 3.420      | 0.0194     | POL vs PMC    | 0.1  | 0.1   | 0.2  | 4.979 | <0.001 |
|                   | POL vs PMC         | 0.1  | 0.1   | 0.2  | 6.526      | <0.001     |                      |       |       |       |       |       |
| 90                | Comparisons to Intact |       |       |       |             |     |       |       |             |     |       |       |
|                   | PLT/PFL vs ALL/LC   | 0.5  | 0.3   | 0.7  | 5.055      | 0.0027     | PMC vs Intact | 0.2  | 0.1   | 0.3  | 3.906 | 0.0102 |
|                   | ALL/LC vs ITB      | 5.4  | 3.1   | 7.6   | 5.421      | 0.0021     | POL vs Intact | 0.4  | 0.2   | 0.6  | 5.396 | <0.001 |
|                   | ITB vs AMC         | 0.1  | 0.0   | 0.2  | 2.287      | 0.0656     | ALL/LC vs Intact | 0.5  | 0.3   | 0.7  | 6.308 | <0.001 |
|                   | AMC vs POL         | 0.7  | 0.1   | 1.4  | 2.519      | 0.0656     | POL vs PMC    | 0.2  | 0.1   | 0.3  | 4.757 | 0.0062 |
|                   | POL vs PMC         | 0.1  | 0.0   | 0.2  | 3.233      | 0.0308     |                      |       |       |       |       |       |

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| Flexion Angle | Comparison to Intact | Lateral-to-Medial | Medial-to-Lateral |
|--------------|----------------------|-------------------|-------------------|
|              |                      | Specific Comparison | Mean | 95% CI | Holm P-value |
|              |                      |                | Diff | Lower | Upper | t | p-value |
|              |                      | PMC vs Intact | 0.2 | 0.1 | 0.3 | 4.374 | 0.0054 |
|              |                      | POL vs Intact | 0.4 | 0.3 | 0.5 | 8.815 | <0.001 |
|              |                      | AMC vs Intact | 0.5 | 0.4 | 0.7 | 8.854 | <0.001 |
|              |                      | ITB vs Intact | 0.6 | 0.5 | 0.8 | 8.667 | <0.001 |
|              |                      | ALL/LC vs Intact | 0.7 | 0.6 | 0.9 | 10.702 | <0.001 |
| 0            | Sequential Comparisons | PLT/PFL vs ALL/LC | 0.1 | 0.1 | 0.2 | 4.553 | 0.0069 |
|              |                      | PMC vs Intact | 0.1 | 0.0 | 0.2 | 2.983 | 0.0307 |
| 30           | Sequential Comparisons | PLT/PFL vs ALL/LC | 1.0 | 0.3 | 1.3 | 3.241 | 0.0350 |
|              |                      | PMC vs Intact | 0.1 | 0.0 | 0.2 | 2.630 | 0.0821 |
|              |                      | AMC vs POL | 0.1 | 0.0 | 0.2 | 1.035 | 0.3279 |
|              | Sequential Comparisons | PLT/PFL vs ALL/LC | 2.7 | 1.4 | 4.0 | 4.553 | 0.0092 |
|              |                      | PMC vs Intact | 0.2 | 0.1 | 0.3 | 2.398 | 0.0197 |
|              |                      | ALL/LC vs ITB | 0.2 | 0.1 | 0.3 | 4.880 | 0.0087 |
|              |                      | PMC vs Intact | 0.1 | 0.0 | 0.2 | 2.398 | 0.0197 |
|              | Sequential Comparisons | PLT/PFL vs ALL/LC | 3.7 | 1.9 | 5.4 | 4.701 | 0.0092 |
|              |                      | PMC vs Intact | 0.1 | 0.0 | 0.2 | 2.630 | 0.0821 |
| 60           | Sequential Comparisons | PLT/PFL vs ALL/LC | 3.7 | 1.9 | 5.4 | 4.701 | 0.0092 |
|              |                      | PMC vs Intact | 0.2 | 0.1 | 0.3 | 2.398 | 0.0197 |
| 90           | Sequential Comparisons | PLT/PFL vs ALL/LC | 2.9 | 1.9 | 3.9 | 4.444 | <0.001 |
|              |                      | PMC vs Intact | 0.3 | 0.1 | 0.4 | 2.398 | 0.0197 |
|              |                      | ALL/LC vs ITB | 3.2 | 2.0 | 4.3 | 6.117 | 0.0011 |
|              |                      | PMC vs Intact | 0.2 | 0.1 | 0.3 | 2.398 | 0.0197 |
|              |                      | ALL/LC vs ITB | 4.1 | 2.8 | 5.3 | 7.261 | <0.001 |
|              |                      | PMC vs Intact | 0.1 | 0.0 | 0.2 | 2.398 | 0.0197 |