Effect of Meniscocapsular and Meniscotibial Lesions in ACL-Deficient and ACL-Reconstructed Knees

A Biomechanical Study

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Background: Ramp lesions were initially defined as a tear of the peripheral attachment of the posterior horn of the medial meniscus at the meniscocapsular junction. The separate biomechanical roles of the meniscocapsular and meniscotibial attachments of the posterior medial meniscus have not been fully delineated.

Purpose: To evaluate the biomechanical effects of meniscocapsular and meniscotibial lesions of the posterior medial meniscus in anterior cruciate ligament (ACL)–deficient and ACL-reconstructed knees and the effect of repair of ramp lesions.

Study Design: Controlled laboratory study.

Methods: Twelve matched pairs of human cadaveric knees were evaluated with a 6 degrees of freedom robotic system. All knees were subjected to an 88-N anterior tibial load, internal and external rotation torques of 5 N·m, and a simulated pivot-shift test of 10-N valgus force coupled with 5-N·m internal rotation. The paired knees were randomized to the cutting of either the meniscocapsular or the meniscotibial attachments after ACL reconstruction (ACLR). Eight comparisons of interest were chosen before data analysis was conducted. Data from the intact state were compared with data from the subsequent states. The following states were tested: intact (n = 24), ACL deficient (n = 24), ACL deficient with a meniscocapsular lesion (n = 12), ACL deficient with a meniscotibial lesion (n = 12), ACL deficient with both meniscocapsular and meniscotibial lesions (n = 24), ACLR with both meniscocapsular and meniscotibial lesions (n = 16), and ACLR with repair of both meniscocapsular and meniscotibial lesions (n = 16). All states were compared with the previous states. For the repair and reconstruction states, only the specimens that underwent repair were compared with their intact and sectioned states, thus excluding the specimens that did not undergo repair.

Results: Cutting the meniscocapsular and meniscotibial attachments of the posterior horn of the medial meniscus significantly increased anterior tibial translation in ACL-deficient knees at 30° ($P \leq .020$) and 90° ($P < .005$). Cutting both the meniscocapsular and meniscotibial attachments increased tibial internal (all $P > .004$) and external (all $P < .001$) rotation at all flexion angles in ACL-reconstructed knees. Reconstruction of the ACL in the presence of meniscocapsular and meniscotibial tears restored anterior tibial translation ($P > .053$) but did not restore internal rotation ($P < .002$), external rotation ($P < .002$), and the pivot shift ($P < .05$). To restore the pivot shift, an ACLR and a concurrent repair of the meniscocapsular and meniscotibial lesions were both necessary. Repairing the meniscocapsular and meniscotibial lesions after ACLR did not restore internal rotation and external rotation at angles >30°.

Conclusion: Meniscocapsular and meniscotibial lesions of the posterior horn of the medial meniscus increased knee anterior tibial translation, internal and external rotation, and the pivot shift in ACL-deficient knees. The pivot shift was not restored with an isolated ACLR but was restored when performed concomitantly with a meniscocapsular and meniscotibial repair. However, the effect of this change was minimal; although statistical significance was found, the overall clinical significance remains unclear. The ramp lesion repair used in this study failed to restore internal rotation and external rotation at higher knee flexion angles. Further studies should examine improved meniscus repair techniques for root tears combined with ACLRs.

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Clinical Relevance: Meniscal ramp lesions should be repaired at the time of ACLR to avoid continued knee instability (anterior tibial translation) and to eliminate the pivot-shift phenomenon.

Keywords: knee; meniscus; biomechanics; ramp lesion

There has been increasing interest in the biomechanical and clinical effects of lesions of the posterior horn of the medial meniscus, specifically tears at the meniscocapsular junction (termed "ramp" lesions), which have been reported to be present in 9% to 17% of all anterior cruciate ligament (ACL) tears.[2,5,13] Ramp lesions were initially defined as a tear of the peripheral attachment of the posterior horn of the medial meniscus at the meniscocapsular junction.[2,21] However, recent literature suggested that ramp lesions might actually be due to an injury to the meniscotibial ligament attachment to the posterior horn of the medial meniscus.[16,18,19] The meniscotibial ligament is an attachment that originates on the posterior tibia and inserts on the inferior surface of the posterior horn of the medial meniscus.[16,19] The inconsistency in the definition is also a result of the difficulty in diagnosing these tears on magnetic resonance imaging.[2,5,19]

The medial meniscus has been reported to have an essential role in stabilizing the knee in chronically ACL-deficient knees.[1,3,15,17] Posterior medial meniscal tears are reported to increase knee instability in ACL-deficient knees.[1,20] An understanding of the biomechanical effects of tears to the meniscocapsular attachment (MCA) and the meniscotibial attachment (MTA) of the posterior aspect of the medial meniscus in ACL-deficient and ACL-reconstructed knees is still lacking. This information is important in understanding ramp lesions and the roles of the posterior medial meniscal attachments on knee stability. There is controversy over the definition of ramp lesions and whether ramp lesions affect knee kinematics in ACL-reconstructed knees. Persistent instability after ACL reconstruction (ACLR) because of unaddressed concomitant medial meniscal injury will potentially increase forces on the ACL graft, ultimately leading to failure.[1,15,20]

Furthermore, research regarding the biomechanical effectiveness of meniscal ramp repair is limited and has been reported on an all-inside repair technique[20]; however, an inside-out repair has yet to be studied biomechanically for these lesions. Thus, the purpose of this study was to assess the biomechanical effects of sectioning the MCA and MTA of the posterior horn of the medial meniscus in ACL-deficient and ACL-reconstructed knees. We hypothesized that there would be increased anterior tibial translation (ATT) and rotational instability during simulated Lachman testing, pivot-shift testing, and internal/external rotation testing in the presence of untreated medial meniscal ramp lesions and that a repair would restore knee kinematics.

METHODS

Specimen Preparation

Twelve matched pairs (n = 24) of fresh-frozen male cadaveric knee specimens (mean age, 61.0 years; range, 54-66 years) with no evidence of prior injury, previous surgery, osteoarthritis, or meniscus or ligament injury were used for 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 before preparation. Before testing, each specimen underwent a diagnostic arthroscopy to confirm the absence of intra-articular pathology. The posterior horn of the medial meniscus was visualized through a standard anterolateral portal and an accessory posteromedial portal.

In preparation for potting, the tibial, fibular, and femoral diaphyses were cut 20 cm from the joint line. Sharp dissection to bone was performed; 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 PMMA (polymethyl methacrylate; Fricke Dental International Inc). 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

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Figure 1. Schematic representation of the robotic setup with the inverted knee mounted in the testing system.

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, 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, at the medial and lateral femoral epicondyles, and along the tibial diaphysis.[12,25] The coordinate system defined the knee joint center of rotation and the anterior-posterior, medial-lateral, and superior-inferior axes. Before testing, each 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 10-N compressive load was applied along the axis of the tibial shaft to ensure tibiofemoral contact throughout testing. This robotic testing setup was previously described and validated for knee joint kinematic testing.[10,11] The average time of testing for 1 specimen was approximately 4 hours.

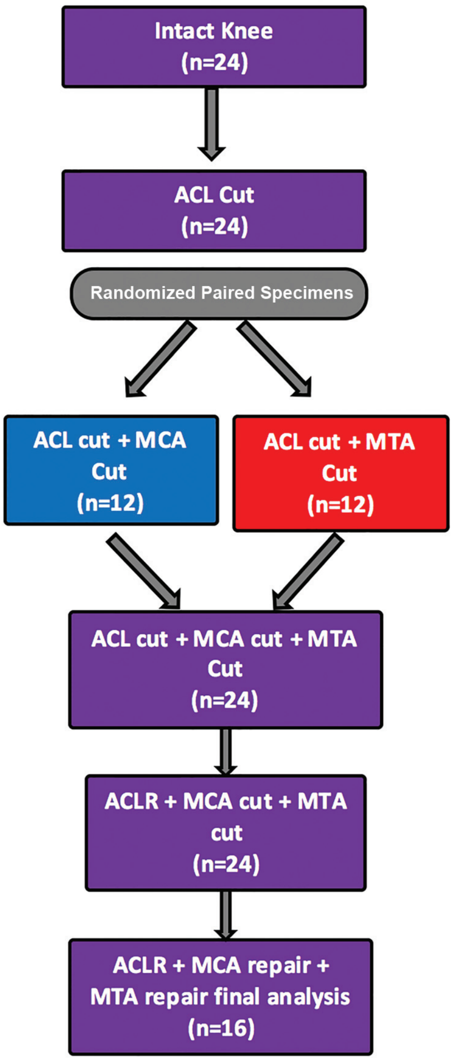

Figure 2. Flowchart depicting the order of biomechanical testing states for all specimens per randomization. ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; MCA, meniscocapsular attachment; MTA, meniscotibial attachment.

Biomechanical Testing

The intact state was tested first in all knees, followed by the ACL cut state. The knees of each pair were then randomly assigned to either cutting MTA first or MCA first, after the ACL sectioning. For knees that underwent MTA sectioning first, the MCA was sectioned next, and for those that underwent meniscocapsular sectioning first, the MTA was sectioned next such that all knees had both the MTA and the MCA sectioned. The ACL was then reconstructed in all knees, followed by repair of the MCA and MTA. The following states were tested: intact (n = 24), ACL deficient (n = 24), ACL deficient with a meniscocapsular lesion (n = 12), ACL deficient with a meniscotibial lesion (n = 12), ACL deficient with both meniscocapsular and meniscotibial lesions (n = 24), ACLR with both meniscocapsular and meniscotibial lesions (n = 16), and ACLR with repair of both meniscocapsular and meniscotibial lesions (n = 16). After the first 8 specimens were tested, all specimens underwent a posttest arthrotomy to assess the success of the outside-in repair technique utilized. In all 8 specimens, the repairs were found to have failed, and the repair technique was switched to an inside-out repair in the robot. Posttesting arthrotomy of all remaining specimens (n = 16) demonstrated a successful repair of the meniscocapsular and meniscotibial lesion. The postrepair testing of the initial 8 specimens was not included in the final analysis (ACLR, MCA repair, MTA repair) (Figure 2).

The knees were subjected to the following testing conditions: anterior tibial load of 88 N, internal and external rotation torques of 5 N·m, and a simulated pivot-shift test of 10-N valgus force coupled with 5-N·m internal rotation torque as previously described.[8] ATT was tested at 30° and 90°, simulated pivot-shift test at 15° and 30°, and internal/external rotation at 0° to 90° with 15° increments. For each state, anterior tibial displacement, internal rotation, and external rotation were compared with the intact state for all testing conditions.

Surgical Technique

An anatomic single-bundle ACLR was performed in all specimens as previously described.[10] The ACL was reconstructed with a bone–patellar tendon–bone allograft with 10-mm bone blocks. To create an MCA lesion, the knee was flexed to 90°; a scalpel was then inserted through the posteromedial portal; and a tear was made in the meniscocapsular junction, extending 2.5 cm medially from the medial meniscal root attachment. The meniscocapsular lesion was repaired with an arthroscopic-assisted inside-out technique with 4 to 6 meniscal sutures (No. 2 FiberWire; Arthrex, Inc) with the knee in the robot at 90° of flexion (Figure 3).

To simulate the MTA lesion, a longitudinal posterior approach was performed with a dissection made between the gastrocnemius muscle heads. The posterior capsule, oblique popliteal ligament, champagne glass drop-off, and the semimembranosus tendon were visualized. A horizontal incision was made through the distal capsule, medial to the posterior cruciate ligament tibial facet and 1.5 cm distal to the joint line. The MTA was detached with a scalpel from this point to the level of the semimembranosus tibial attachment on the tibia (Figure 4). The meniscotibial lesion was repaired with the knee in full extension, with 2 suture anchors (SwiveLock; Arthrex, Inc) placed in the proximal aspect of the medial tibial plateau and reinforced with 2 No. 2 FiberWire sutures to restore the MTA (Figure 5). All meniscal lesions, repairs, and ACLRs were performed by 2 board-certified orthopaedic surgeons (G.M., J.C.) with experience in arthroscopy and meniscal surgery. The same 2 board-certified surgeons have performed several knee biomechanical studies and anatomy studies.

Statistical Analysis

Eight comparisons of interest were chosen before data analysis was conducted (Table 1). For this study, statistical power was considered in the context of a detectable effect size (Cohen *d*), given the fixed study design and sample size. Based on an overall alpha level of .05 with Bonferroni correction for 8 comparisons and 2-tailed testing, repeated measures comparisons of group means involving 12, 16, and 24 specimens are sufficient to detect effect sizes of 1.29, 1.06, and 0.82 with 80% statistical power, respectively.

Data were analyzed after subtracting each specimen's intact values. For the repair and reconstruction states, only the specimens that underwent repair were compared with their intact and sectioned states, thus excluding the specimens that did not undergo repair. Because all measurement variables were reasonably normally distributed and the comparisons included different sample sizes, paired *t* tests were used to make all comparisons among knee conditions. The Holm method was used to control the family-wise type I error rate to .05 within each experiment and flexion angle combination, and Holm-adjusted P values were presented. The design of the experiment is presented in Figure 2. Adjusted P values $<.05$ were deemed statistically significant. The statistical software R was used for all analyses (R Foundation for Statistical Computing with *ggplot2*).[7]

RESULTS

ATT During an 88-N Anterior Load

Cutting the MCA significantly increased ATT in ACL-deficient knees by 0.5 mm and 0.8 mm at 30° and 90°, respectively (both $P < .005$). Cutting the MTA significantly increased ATT in ACL-deficient knees but to a lesser degree (Table 2). Cutting both the MCA and MTA significantly increased ATT in ACL-deficient knees ($P < .001$). Reconstruction of the ACL in the presence of MCA and MTA tears restored ATT relative to the intact state at both 30° and 90° (both $P > .05$).

Internal Tibial Rotation During a 5-N·m Internal Rotation Torque

Cutting the MCA significantly increased tibial internal rotation between 30° and 90° (all $P < .04$), while cutting the MTA increased internal tibial rotation at all flexion angles (all $P < .005$) in ACL-deficient knees. Cutting both the MCA and MTA significantly increased internal rotation at all flexion angles (all $P < .001$) (Appendix Table A1, available in the online version of this article). Reconstruction of the ACL in the presence of meniscocapsular and meniscotibial lesions did not restore internal rotation (all $P < .003$). Anterior cruciate reconstruction with repair of the MCA and MTA restored internal rotation to the intact state at 0° to 15° but did not at 30° to 90° (all $P < .001$) (Figure 6).

External Tibial Rotation During a 5-N·m External Rotation Torque

Cutting the MCA significantly increased tibial external rotation by 0.7° to 1.0° at all flexion angles (all $P < .004$),

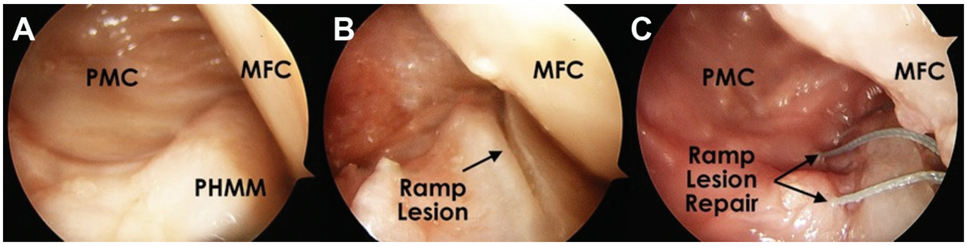

Figure 3. Arthroscopic image of a meniscocapsular lesion. (A) Intact meniscocapsular junction with camera inserted through the intercondylar notch. (B) With an accessory posteromedial portal, a scalpel was inserted and used to re-create a meniscocapsular tear. (C) Inside-out meniscal repair with sutures placed in a vertical mattress fashion, first through the posterior horn of the medial meniscus and second through the posteromedial capsule. MFC, medial femoral condyle; PHMM, posterior horn medial meniscus; PMC, posteromedial capsule.

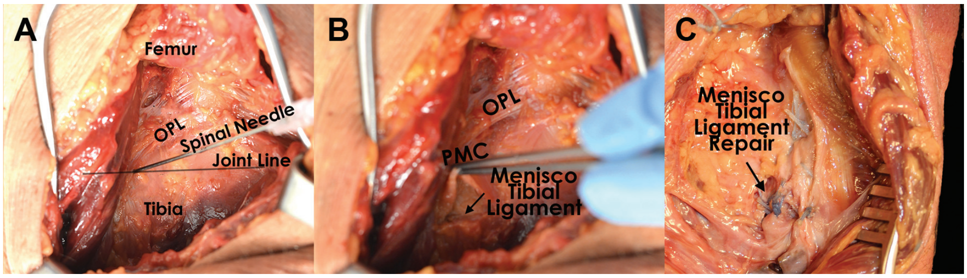

Figure 4. Open image of a meniscotibial lesion. (A) Open posterior dissection with intact meniscotibial ligament and pertinent landmarks. (B) To identify the meniscotibial ligament, an 18-gauge spinal needle was inserted into the posteromedial joint line, and an incision was made approximately 1 cm medial to the posterior cruciate ligament tibial facet and 1.5 cm from the joint line. A scalpel was then inserted directly inferior to the meniscus, and a cut was made on the fibers attaching the meniscus to the tibia to re-create a meniscotibial ligament tear. (C) Open posterior repair of the meniscotibial attachment with the knee in full extension with 2 suture anchors placed in the proximal aspect of the medial tibial plateau. OPL, oblique posterior ligament; PMC, posteromedial capsule.

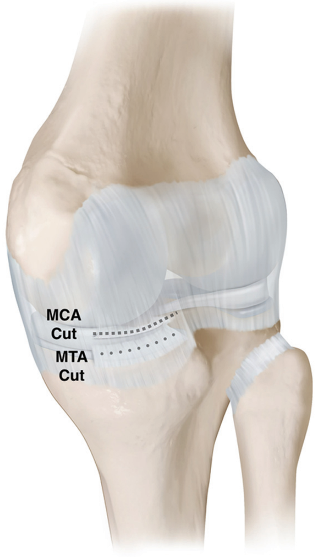

Figure 5. Illustration of the tear locations for the meniscocapsular and meniscotibial attachments. MCA, meniscocapsular attachment; MTA, meniscotibial attachment.

TABLE 1
Comparison of Test States for Statistical Analysis[a]

	n[b]
ACL cut, MCA and MTA intact	
ACL cut, MCA cut, MTA intact	12
ACL cut, MTA cut, MCA intact	12
ACL cut, MCA and MTA cut	24
ACLR, MCA and MTA cut	
ACL cut, MCA and MTA cut	24
ACLR, MCA and MTA repair	16
ACL cut, MCA and MTA cut: ACLR, MCA and MTA repair	16
Intact knee	
ACLR, MCA and MTA cut	24
ACLR, MCA and MTA repair	16

[a] The meniscus repair failed in 8 knees; thus, 16 knees were analyzed for final MCA and MTA repair. ACL, anterior cruciate ligament, ACLR, anterior cruciate ligament reconstruction; MCA, meniscocapsular attachment; MTA, meniscotibial attachment.

[b] The number of specimens used in a given repeated measures comparison.

TABLE 2
Anterior Tibial Translation During an 88-N Anterior Tibial Load for the Different Testing States[a]

	Anterior Tibial Translation,[b] mm			
	MCA 30°	MCA 90°	MTA 30°	MTA 90°
Intact (n = 24)	6.7 ± 2.4	4.5 ± 2.0	5.7 ± 1.7	3.9 ± 1.7
ACL cut (n = 24)	9.1 ± 3.4	5.1 ± 2.1	9.1 ± 2.9	5.7 ± 2.7
ACL cut + meniscocapsular cut + meniscotibial intact (n = 12)	9.9 ± 3.6	5.6 ± 2.3	NA	NA
ACL cut + meniscocapsular intact + meniscotibial cut (n = 12)	NA	NA	9.4 ± 3.0	5.9 ± 2.7
ACL cut + meniscocapsular cut + meniscotibial cut (n = 24)	10.2 ± 3.7	5.8 ± 2.4	9.8 ± 3.1	6.2 ± 2.9
ACLR + meniscocapsular cut + meniscotibial cut (n = 24)	–0.6 ± 1.7	1.0 ± 1.0	–0.3 ± 1.0	0.3 ± 1.4
ACLR + meniscocapsular repair + meniscotibial repair (n = 16)	–0.5 ± 1.8	0.9 ± 1.3	–0.3 ± 0.9	0.1 ± 1.3

[a] All values (mean ± SD) are reported as intact subtracted, with negative values interpreted as less knee motion as compared with the intact. In the MCA group, the MCA was sectioned first, followed by the MTA. In the MTA group, the MTA was sectioned first, followed by the MCA. The meniscus repair failed in 8 knees; thus, 16 knees were analyzed for final MCA and MTA repair. ACL, anterior cruciate ligament, ACLR, anterior cruciate ligament reconstruction; MCA, meniscocapsular attachment; MTA, meniscotibial attachment; NA, not applicable.

[b] By testing group and knee flexion angle.

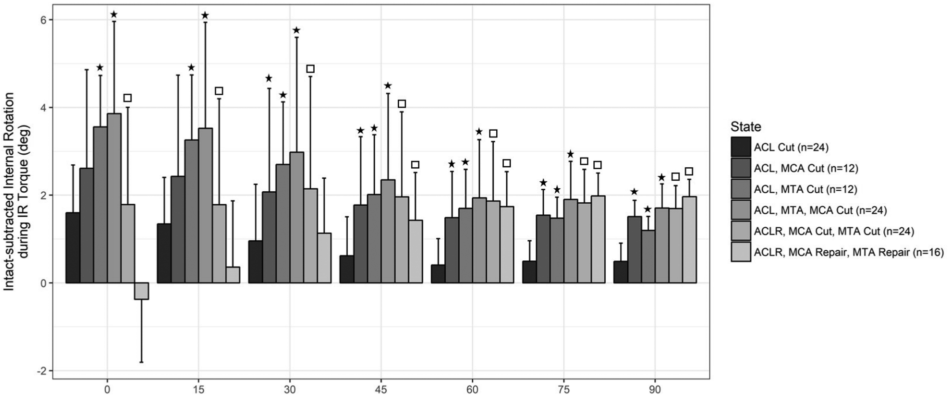

Figure 6. Changes in tibial internal rotation (IR) during a 5-N·m IR torque for the different testing states. ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; MCA, meniscocapsular attachment; MTA, meniscotibial attachment. An asterisk (*) indicates a significant difference from the ACL-deficient state. The ACLR and repair states were compared with the intact state, and a square (□) indicates significant difference versus the intact state. Values (mean ± SD) are presented as intact subtracted, with negative values interpreted as less knee motion as compared with the intact.

and cutting the MTAs also increased external tibial rotation at all flexion angles (all $P < .001$) in ACL-deficient knees. Cutting both the MCA and MTA significantly increased external tibial rotation at all flexion angles (all $P < .001$) as compared with the intact state (Table 3). Reconstruction of the ACL in the presence of meniscocapsular and meniscotibial lesions did not restore tibial external rotation to intact state at all flexion angles (all $P < .003$). Reconstruction of the ACL and repair of meniscocapsular and meniscotibial lesions overconstrained the knee at 0° and restored external rotation to the intact state at 15° but not from 30° to 90° (Figure 7).

Simulated Pivot-Shift Test

Cutting either the MCA or the MTA in ACL-deficient knees significantly increased ATT and internal rotation during a simulated pivot-shift test at 15° and 30° of knee flexion (Table 4). Cutting both the MCA and the MTA significantly increased ATT and internal rotation during a simulated pivot-shift test in ACL-deficient knees (all $P < .001$). Reconstruction of the ACL alone in the presence of meniscocapsular and meniscotibial lesions did not restore pivot shift to the intact state ($P < .05$). Reconstruction of the ACL and repair of the meniscocapsular and meniscotibial lesions restored ATT during a pivot-shift test to a near-intact state at 15° ($P > .99$) and 30° ($P = .116$). Reconstruction of the ACL and repair of the meniscocapsular and meniscotibial lesions restored internal rotation during a simulated pivot-shift test to the intact state at 15° ($P = .309$) but not at 30° ($P < .001$).

DISCUSSION

The main findings of this study were that tears to both the MCA and the MTA of the posterior horn of the medial meniscus resulted in increased ATT, internal rotation,

TABLE 3
Tibial External Rotation During a 5-N·m External Rotation Torque for the Different Testing States[a]

	Group	External Rotation,[b] deg						
		0°	15°	30°	45°	60°	75°	90°
ACL cut (n = 12)	MCA	−0.2 ± 0.3	−0.3 ± 0.4	−0.1 ± 0.3	−0.2 ± 0.3	−0.1 ± 0.4	−0.4 ± 0.4	−0.4 ± 0.5
ACL cut (n = 12)	MTA	−0.2 ± 0.2	−0.1 ± 0.3	−0.4 ± 0.4	−0.2 ± 0.5	−0.3 ± 0.4	−0.3 ± 0.4	−0.4 ± 0.5
ACL cut + meniscocapsular cut + meniscotibial intact (n = 12)	MCA	−1 ± 0.4	−1 ± 0.5	−1.1 ± 0.5	−1.1 ± 0.5	−1.1 ± 0.5	−1.3 ± 0.8	−1.4 ± 0.6
ACL cut + meniscocapsular intact + meniscotibial cut (n = 12)	MTA	−0.9 ± 0.3	−0.8 ± 0.4	−0.9 ± 0.5	−0.9 ± 0.5	−0.9 ± 0.5	−0.9 ± 0.6	−1 ± 0.6
ACL cut + meniscocapsular cut + meniscotibial cut (n = 12)	MCA	−1.5 ± 0.9	−1.5 ± 0.9	−1.5 ± 0.9	−1.4 ± 0.7	−1.4 ± 0.6	−1.6 ± 0.9	−1.7 ± 1
ACL cut + meniscocapsular cut + meniscotibial cut (n = 12)	MTA	−1 ± 0.4	−1 ± 0.5	−1.1 ± 0.5	−1.2 ± 0.6	−1.2 ± 0.6	−1.3 ± 0.7	−1.3 ± 0.8
ACLR + meniscocapsular cut + meniscotibial cut (n = 12)	MCA	−1.1 ± 0.8	−1.2 ± 0.8	−1.4 ± 0.9	−1.4 ± 0.8	−1.5 ± 0.7	−1.7 ± 0.9	−1.8 ± 1.1
ACLR + meniscocapsular cut + meniscotibial cut (n = 12)	MTA	−0.7 ± 0.6	−0.7 ± 0.8	−1.1 ± 0.5	−1.1 ± 0.4	−1.3 ± 0.6	−1.3 ± 0.7	−1.4 ± 0.8
ACLR + meniscocapsular repair + meniscotibial repair (n = 8)	MCA	1.7 ± 1.4	0.2 ± 1	−0.8 ± 0.5	−1 ± 0.5	−1.2 ± 0.5	−1.5 ± 1	−1.5 ± 0.8
ACLR + meniscocapsular repair + meniscotibial repair (n = 8)	MTA	0.6 ± 1.1	−0.3 ± 1.1	−0.8 ± 0.7	−0.9 ± 0.6	−1.1 ± 0.8	−1.1 ± 1.1	−1.2 ± 1.2

[a] All values (mean ± SD) are reported as intact subtracted, with negative values interpreted as less knee motion as compared with the intact. In the MCA group, the MCA was sectioned first, followed by the MTA. In the MTA group, the MTA was sectioned first, followed by the MCA. The meniscal repair failed in 8 knees; thus, 16 knees were analyzed for final MCA and MTA repair. ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; MCA, meniscocapsular attachment group; MTA, meniscotibial attachment group.

[b] By knee flexion angle.

external rotation, and pivot shift in ACL-deficient knees. Patients with high-grade Lachman and pivot-shift test results in the presence of an ACL tear and those with persistent instability after an ACLR should be evaluated for a potential ramp lesion of the posterior horn of the medial meniscus. In addition, the repair technique used in this study could restore the pivot shift at lower flexion angles, yet it failed to restore internal and external rotation at higher flexion angles. Future research should evaluate different repair techniques that can further restore rotational stability at higher flexion angles.

Meniscal ramp lesions have been defined as vertical tears in the meniscocapsular junction associated with ACL tears, and recent studies suggest detrimental effects in knee stability if these lesions are not addressed at time of surgery. Muriuki et al[14] described changes in tibiofemoral contact pressures after vertical tears of the posterior horn of the medial meniscus as compared with radial split tears. The authors concluded that vertical tears of the medial meniscus increased contact pressure and reduced contact area in the medial and lateral compartments, with no difference as compared with a total medial meniscectomy. In 2001, Papageorgiou et al[15] demonstrated the biomechanical interdependence between the ACL-reconstructed graft and the medial meniscus. They reported increased force up to 54% in the ACL-reconstructed graft after a medial meniscectomy, further advocating the potential for increased ACL graft failure with medial meniscal deficiency. Recent data suggest that medial meniscocapsular tears, when left untreated, predispose the ACL-reconstructed knee to increased ATT and potential increased strain in the ACL-reconstructed graft[20] (unpublished data, C. Edgar, MD, PhD, 2015).

In the present study, cutting the MCA and MTA significantly increased ATT in ACL-deficient knees. Ahn et al[1] evaluated the effect of sectioning the MCA and reported significant increases in ATT at all flexion angles except 90°, and this was improved after repair of the lesions, supporting the findings of the present study that meniscocapsular lesions increase instability in ACL-deficient knees. Interestingly, in the study by Ahn et al, lesions of the MCA resulted in comparable changes in ATT in ACL-deficient knees to total medial meniscectomy. These findings were supported by Stephen et al,[20] who reported increased ATT after creation of meniscocapsular lesions in ACL-deficient knees, which were not restored by ACLR alone. Repair of the meniscocapsular lesions and ACLR were necessary to restore knee kinematics. However, in the present study, ACLR restored ATT to a near intact state. Peltier et al[16] reported an increase in ATT during anterior tibial load after sectioning of the ACL, MCA, and MTA, as compared with the intact state. However, sectioning the MCA and MTA in ACL-deficient knees did not significantly change ATT.[16] The authors reported an increase of 2.6 mm in ATT after sectioning the MCA in ACL-deficient knees, but this was not statistically significant. In contrast, the current study reports a significant increase of 0.8 mm of ATT for the same states. This statistical discrepancy can perhaps be explained by the total sample size used in each study (n = 9 vs n = 16) and by the measurement devices used (Rolimeter with manual forces vs a 6 degrees of freedom

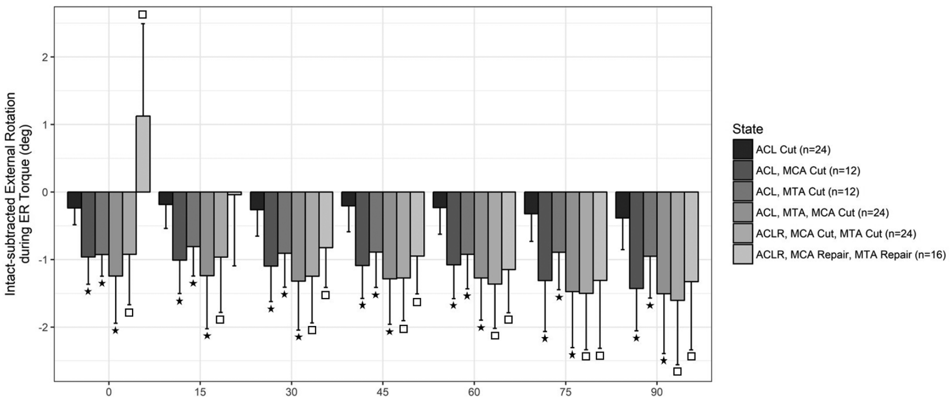

Figure 7. Changes in tibial external rotation (ER) during a 5-N·m ER torque for the different states. ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; MCA, meniscocapsular attachment; MTA, meniscotibial attachment. An asterisk (*) indicates a significant difference from the ACL-deficient state. The ACLR and repair states were compared with the intact state, and a square (□) indicates significant difference versus the intact state. Values (mean ± SD) are presented as intact subtracted, with negative values interpreted as less knee motion as compared with the intact.

robotic system). Previous research showed a side-to-side difference as small as 3 mm with a maximum manual force with a KT-1000 arthrometer to be indicative of ACL tears[9,23]; thus, the 0.8 mm achieved with an 88-N load in the current study seems practical for increased ATT. However, the ACL is the primary stabilizer for ATT, and when it is adequately reconstructed, the changes in ATT after creation of a ramp lesion may not be significant as observed in the present study.

Cutting both the MCA and the MTA of the posterior horn of the medial meniscus significantly increased internal rotation, external rotation, and pivot shift in ACL-deficient knees. These findings suggest that injuries to the MCA and/or MTA of the medial meniscus can cause increased knee rotation and translation. In the present study, ACLR in the presence of meniscocapsular and meniscotibial lesions did not restore pivot shift, which was restored only after an ACLR was performed and the meniscocapsular and meniscotibial lesions were repaired. These findings imply that patients with an ACL tear and a concomitant ramp lesion may have a high-grade pivot shift on examination, and if the meniscal lesion is not repaired during ACLR, these patients may have persistent rotational instability. The medial meniscus is firmly attached to the posterior margin of the tibial plateau,[24] resulting in the meniscus acting as a secondary stabilizer for anterior translation and tibial rotation in ACL-deficient knees. Peltier et al[16] reported significantly increased tibial internal rotation and external rotation after sectioning both the MCA and the MTA. Ahn et al[1] reported no significant change in tibial rotation after creating a meniscocapsular lesion in an ACL-deficient knee. Studies by Ahn et al[1] and Peltier et al[16] focused on ACL-deficient knees—as opposed to ACL-reconstructed knees in the present study (because most surgeons reconstruct ACLs)—but there is a controversy over the repair of ramp lesions. Stephen et al[20] reported no significant change in internal rotation after creating a meniscocapsular lesion in ACL-deficient knees; however, external rotation was increased across all flexion angles in the same testing state. These were restored after repair of the meniscocapsular lesion. In the present study, repair of the meniscocapsular and meniscotibial lesions did not restore internal and external tibial rotations at angles >30°. It is possible that our repair did not restore internal/external rotation at angles >30° because the meniscocapsular lesions were not fixed in full knee extension. Fixing the meniscocapsular lesion in extension with an inside-out repair with a patient in the supine position can be challenging. Tying the sutures at 90° better reflects what is performed in surgery with a meniscocapsular repair with the patient supine. However, since the skin and other soft tissues were not present and thus would not limit exposure as they would clinically, it is probable that our repair was more secure and taut than what would be created clinically. Furthermore, of clinical importance, the meniscotibial lesion was repaired with the knee near full extension, with the capsule taut. Future studies should examine improved meniscus repair techniques for ramp lesions combined with ACLRs.

There is still controversy about the definition of a ramp lesion. Smigielski et al[18] reported that the superior part of the medial meniscal posterior horn had no capsular attachment, while the inferior part was attached to the tibia via the meniscotibial ligament. This led some authors to argue that ramp lesions involve the MTA of the medial meniscus.[16] It is also not clearly defined in the literature whether ramp lesions are complete or partial tears of the peripheral posterior horn.[22] Complete tears could have similar biomechanical effects to tears involving the MTA because of the loss of the bony attachment from the meniscus to the tibia, resulting in meniscal displacement. Biomechanical studies have used different methods of creating meniscocapsular lesions, which can lead to different findings.[1,20] It is also possible that ramp lesions are not all the same, and a thorough evaluation of each tear should be performed. Furthermore, more studies are needed to

TABLE 4
Changes in ATT and Tibial IR During a Simulated Pivot-Shift Test for the Different Testing States at 15° and 30° of Knee Flexion[a]

	Pivot Shift (ATT),[b] mm			
	MCA 15°	MCA 30°	MTA 15°	MTA 30°
ACL cut (n = 24)	1.5 ± 1.7	0.9 ± 1.8	1.4 ± 0.9	1.0 ± 0.7
ACL cut + meniscocapsular cut + meniscotibial intact (n = 12)	2.6 ± 2.6	2.0 ± 2.6	NA	NA
ACL cut + meniscocapsular intact + meniscotibial cut (n = 12)	NA	NA	3.6 ± 1.9	2.9 ± 1.8
ACL cut + meniscocapsular cut + meniscotibial cut (n = 24)	3.9 ± 3.5	3.0 ± 3.6	3.8 ± 1.9	3.1 ± 1.9
ACLR + meniscocapsular cut + meniscotibial cut (n = 24)	2.7 ± 3.6	3.0 ± 3.6	2.3 ± 1.9	2.8 ± 1.8
ACLR + meniscocapsular repair + meniscotibial repair (n = 16)	0.6 ± 1.8	2.0 ± 1.6	1.0 ± 1.6	1.9 ± 1.1
	Pivot Shift (IR),[b] deg			
ACL cut (n = 24)	4.4 ± 3.0	3.6 ± 4.0	4.6 ± 1.7	4.0 ± 1.9
ACL cut + meniscocapsular cut + meniscotibial intact (n = 12)	5.2 ± 3.6	4.4 ± 4.4	NA	NA
ACL cut + meniscocapsular intact + meniscotibial cut (n = 12)	NA	NA	5.7 ± 1.8	4.8 ± 2.2
ACL cut + meniscocapsular cut + meniscotibial cut (n = 24)	6.0 ± 4.1	4.9 ± 4.7	6.0 ± 1.8	5.3 ± 2.3
ACLR + meniscocapsular cut + meniscotibial cut (n = 24)	1.5 ± 3.7	2.0 ± 3.6	1.4 ± 1.9	2.0 ± 1.7
ACLR + meniscocapsular repair + meniscotibial repair (n = 16)	–0.7 ± 2.7	1.2 ± 2.7	0.1 ± 1.6	1.3 ± 1.3

[a] All values (mean ± SD) are reported as intact subtracted, with negative values interpreted as less knee motion compared with the intact. In the MCA group, the MCA was sectioned first, followed by the MTA. In the MTA group, the MTA was sectioned first, followed by the MCA. The meniscus repair failed in 8 knees; thus, 16 knees were analyzed for final MCA and MTA repair. ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; ATT, anterior tibial translation; IR, internal rotation; MCA, meniscocapsular attachment; MTA, meniscotibial attachment; NA, not applicable.

[b] By testing group and knee flexion angle.

elucidate the anatomy of the menisci and the attachments of the medial meniscus to the capsule and tibia.

Meniscal ramp repair has been described with all-inside devices,[20] a hybrid technique with all-inside and outside-in repair via an accessory posteromedial portal,[22] and an inside-out repair technique.[6] Inside-out repair was reported to allow for more versatility in repairing the meniscus with an arguably stronger construct, because the meniscus is sutured directly to the capsule.[4,6] A previous laboratory study demonstrated that an all-inside repair technique for meniscal ramp lesions was able to restore knee kinematics.[20] In contrast, the repair techniques (inside-out meniscocapsular and open meniscotibial) utilized in the current study failed to restore knee kinematics at higher knee flexion angles. To our knowledge, this is the first biomechanics study to examine the effects of a meniscotibial ligament repair and an inside-out repair of a meniscocapsular lesion. Currently, there is limited understanding on the posterior horn of the medial meniscal stabilizers. In the present study, both the MCA and the MTA were found to have an important role in stabilizing the knee joint. The findings of the current study suggest that it is important to diagnose and treat both meniscocapsular and meniscotibial ramp lesions.

We acknowledge some limitations to this study. Inherent to a time-zero cadaveric study, the results do not reflect the biological incorporation of the ACL graft and its effects on reconstruction performance. The opening in the capsule, which was created to perform the MTA cut, could have contributed to the measured laxity, and this was not measured. Furthermore, the multiple testing conditions may produce certain laxity in the surrounding soft tissue structures. However, this effect was limited by randomizing the order of the testing. In addition, we limited the effect of dependent variables by using the same materials and commercially prepared allografts for every reconstruction. Also, several pilot tests were performed to establish reproducible and highly accurate testing procedures with a 6 degrees of freedom robotic system.

CONCLUSION

Meniscocapsular and meniscotibial lesions of the posterior horn of the medial meniscus increased knee ATT, internal and external rotation, and the pivot shift in ACL-deficient knees. The pivot shift was not restored with an isolated ACLR but was restored when performed concomitantly with a meniscocapsular and meniscotibial repair. However, the effect of this change was minimal; although statistical significance was found, the overall clinical significance remains unclear. The ramp lesion repair failed to restore internal rotation and external rotation at higher knee flexion angles. Further studies should examine improved meniscal repair techniques for root tears combined with ACLRs.

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