Kinematic Analysis of Lateral Meniscal Oblique Radial Tears in Anterior Cruciate Ligament–Reconstructed Knees

Untreated Versus Repair Versus Partial Meniscectomy

Patrick A. Smith,[*†] MD, Will A. Bezold,[‡§] BSE, Cristi R. Cook,[‡§] DVM, MS, Aaron J. Krych,[||] MD, Michael J. Stuart,[||] MD, Coen A. Wijdicks,[¶] PhD, MBA, and James L. Cook,[‡§] DVM, PhD, OTSC
Investigation performed at the Thompson Laboratory for Regenerative Orthopaedics, Department of Orthopaedic Surgery, Missouri Orthopaedic Institute with the University of Missouri, Columbia, Missouri, USA

Background: Lateral meniscal oblique radial tears (LMORTs) affect joint and meniscal stability in anterior cruciate ligament (ACL)–deficient knees.

Purpose: To determine the clinically relevant kinematics associated with the most common posterior horn LMORT lesion types, types 3 (LMORT3) and 4 (LMORT4), untreated versus arthroscopic repair versus partial meniscectomy in combination with ACL reconstruction (ACLR).

Study: Controlled laboratory study.

Methods: Sixteen cadaveric knees underwent robotic testing for anterior drawer and pivot-shift simulations at multiple knee flexion angles in ACL-intact and ACL-deficient states, followed by sequential testing of arthroscopic ACLR, LMORT3 lesion, LMORT3 repair, and partial meniscectomy (n = 8). The same testing sequence was performed for LMORT4 lesions (n = 8).

Results: ACLR restored kinematics in ACL-deficient knees to intact levels for all metrics tested. For anterior drawer, ACLR + LMORT3 tear and partial meniscectomy resulted in significantly greater anterior translation compared with ACL-intact at all angles ($P < .05$) and compared with ACLR at 60° and 90° ($P < .014$). For pivot shift, compared with ACL-intact knees, ACLR + LMORT3 tear resulted in significantly more anterior translation at 15° ($P = .041$); and for ACLR + partial meniscectomy, at both 0° and 15° ($P < .03$). ACLR + LMORT4 tear and partial meniscectomy resulted in significantly greater anterior translation for anterior drawer ($P < .04$) and pivot-shift testing ($P < .05$) compared with intact and ACLR knees at all angles tested. ACLR + LMORT3 repair and ACLR + LMORT4 repair restored kinematics to ACLR and intact levels at all angles tested. ACLR + LMORT3 tear ($P < .008$) and both LMORT4 tear and partial meniscectomy ($P < .05$) resulted in increased meniscal extrusion compared with intact and ACLR statuses at all tested angles for anterior drawer and pivot shift, while repairs restored meniscal stability to ACLR and intact levels.

Conclusion: Untreated LMORT tears increased anterior translation, pivot shift, and meniscal extrusion after ACLR, while partial meniscectomy further exacerbated these detrimental effects in this cadaveric model. In contrast, arthroscopic side-to-side repair of LMORT lesions effectively restored measured knee kinematics.

Clinical Relevance: LMORT lesions are common with ACL tears and adversely affect joint stability and meniscal extrusion. This study highlights the importance of repair of LMORT 3 and 4 lesions at the time of ACLR.

Keywords: lateral meniscal oblique radial tears; meniscal extrusion; meniscal repair; ACL reconstruction

The contributions of the lateral meniscus to knee kinematics and stability have been well documented.[6,9,10,14] These contributions have critical importance in restoring joint health and function after injury, making the high incidence of lateral meniscal tears associated with anterior cruciate ligament (ACL) rupture intensely clinically relevant with respect to recognition and optimal management.[5,15] In that regard, a common lateral meniscal lesion pattern seen with an ACL tear is the posterior horn lateral meniscal oblique radial tear (LMORT). LMORT lesions were recently described based in a 600-patient ACL reconstruction (ACLR) cohort study with an

The American Journal of Sports Medicine
2022;50(9):2381–2389
DOI: 10.1177/03635465221102135

overall incidence of 12%.[11] LMORT type 3 (LMORT3) was described as a radial tear of the posterior horn beginning >10 mm from the root and not extending all the way to the capsule and was reported to represent 30% of LMORT lesions. LMORT type 4 (LMORT4) was defined as a posterior horn radial tear located >10 mm from the root with extension to the capsule and accounted for 48% of LMORTs in the cohort studied.

A previous cadaveric biomechanical study verified the detrimental effects of LMORT 3 or 4 lesions on anterior laxity based on anterior drawer and pivot-shift tests, as well as on lateral meniscal extrusion in the presence of ACL deficiency.[18] As such, these lesions should be considered to have clinical importance with respect to comprehensive management of the ACL-injured knee. Current treatment options for LMORTs include arthroscopic repair, left unrepaired in situ, or partial meniscectomy. The biomechanical effects of partial lateral meniscectomy in ACL-intact and ACL-reconstructed knees are associated with unfavorable joint loading and instability.[16] While some studies support leaving certain posterior horn lateral meniscal tears in the ACL-injured knee untreated,[3,17] more significant tears such as LMORT 3 and 4 lesions can have severe biomechanical consequences on knee kinematics, leading to dysfunction, tear propagation, and secondary osteoarthritis.[15,18,22] However, to our knowledge, a direct comparison of treatment options for LMORT 3 or 4 lesions between tears left untreated, partial meniscectomy, or meniscal repair has not been performed. Therefore, the purpose of this study was to investigate the clinically relevant kinematic effects of LMORT 3 and 4 lesions left untreated in situ versus treated via repair or partial meniscectomy in the ACL-reconstructed knee. The study was designed to test the hypothesis that LMORT 3 and 4 lesions would be associated with significantly increased anterior translation and lateral meniscal extrusion after ACLR, which would be effectively mitigated by arthroscopic meniscal repair but exacerbated by partial meniscectomy.

METHODS

Specimen Preparation and Testing

Consistent with institutional review board policies and guidelines for the use of cadaveric specimens, 16 cadaveric knees (ScienceCare) were tested using an established protocol.[18] For all preparation, testing, and surgical procedures, specimens were maintained at a consistent temperature (20°C-22°C) and kept moistened with isotonic saline. Knees with intact menisci, ligaments, and articular cartilage were prepared by sharply excising soft tissues to circumferentially expose at least 15 cm of femoral and tibial diaphysis. All periarticular tissues were carefully preserved, and the fibular diaphysis was only resected to a level to allow for secure potting of the tibia. Exposed femoral and tibial bone was inserted into aluminum tubing (6.35 cm diameter × 7.62 cm length), and low-temperature metal alloy was poured in the tubing to a 5.08-cm level. After the metal hardened, two 0.32 cm–diameter drill bits were used to drill through tubing, metal, and bone at orthogonal angles to fully secure each bone for each specimen.

After potting, the specimen was mounted to a 6 degrees of freedom robotic testing system (KR 300 R2500 Ultra; KUKA) using custom memory-lock clamps to ensure precise repeatability in sequential mounting position for repetitive testing after status change.[1,8] Anatomic landmarks were digitized using Optotrak Certus (Optotrak; Northern Digital), and a virtual coordinate system was created in the SimVitro software (Version 4.2.0.64; Cleveland Clinic). Using the robotic arm to execute a programmed preconditioning and optimization protocol, we flexed each knee (~0.5 deg/s) from full extension to 90° of knee flexion while recording 6 degrees of freedom forces and torques. The file from the optimization protocol containing the commanded and actual position, force, torque, and velocity raw data was used to verify and optimize the coordinate system for subsequent testing.

*Address correspondence to Patrick A. Smith, MD, Department of Orthopaedic Surgery, University of Missouri, Columbia Orthopaedic Group, 1 S Keene Street, Columbia, MO 65201, USA (email: psmithmudoc@aol.com) (Twitter: @columbiaortho).
†Columbia Orthopaedic Group, Columbia, Missouri, USA.
‡Thompson Laboratory for Regenerative Orthopaedics, University of Missouri, Columbia, Missouri, USA.
§Department of Orthopaedic Surgery, University of Missouri, Columbia, Missouri, USA.
||Department of Orthopaedic Surgery, Mayo Clinic Hospital, Rochester, Minnesota, USA.
¶Department of Orthopedic Research, Arthrex Inc, Naples, Florida, USA.
Submitted November 2, 2021; accepted April 7, 2022.
Presented at the annual meeting of the AOSSM, Colorado Springs, Colorado, July 2022.
One or more of the authors has declared the following potential conflict of interest or source of funding: P.A.S. has received consulting and speaking fees, research support, and royalties including for a product related to the submitted work from Arthrex Inc and owns stock options in Spinal Simplicity. C.R.C. has received royalties, consulting fees, and research support from Arthrex Inc; royalties and consulting fees from CONMED Linvatec; royalties and speaking fees from Musculoskeletal Transplant Foundation and Alpha Orthopedic Systems; research support from Zimmer; and support for education from Medical Device Business Services and Elite Orthopedics. J.L.C. has received consulting fees from Arthrex, Bioventus, and Trupanion; royalties from Arthrex and Musculoskeletal Transplant Foundation (MTF); and research support from Arthrex, DePuy Synthes, GE Healthcare, Merial, MTF, Purina, and Sites Medical. C.R.C. and J.L.C. are husband and wife. A.J.K. has received consulting fees, IP royalties, speaking fees, and research support from Arthrex; research support from Aesculap/B.Braun, Arthritis Foundation, Ceterix, Histogenics; personal fees from Gemini Mountain Medical, LLC, Smith & Nephew; consulting fees from JRF Ortho, Vericel, Responsive Arthroscopy LLC; royalties from Responsive Arthroscopy LLC; honoraria from Vericel and Joint Restoration Foundation; and grant from DJO and Exatech. M.J.S. has received consulting fees and royalties from Arthrex Inc and research support from Stryker Inc and the USA Hockey Foundation. C.W. is a paid employee of Arthrex Inc. AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.

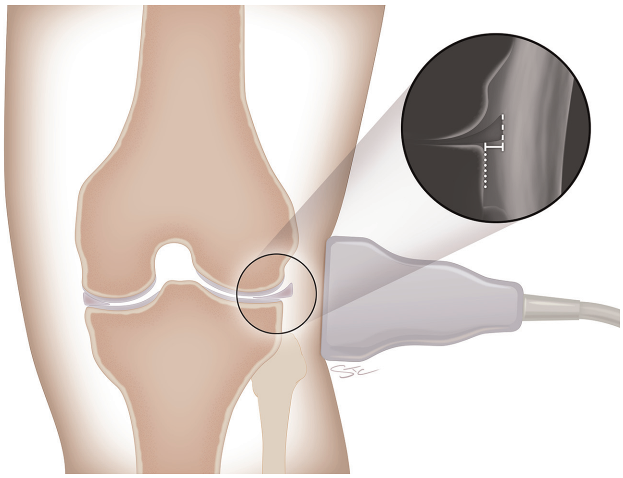

Figure 1. Methodology for ultrasonographic measurement of meniscal extrusion. The dotted line denotes the lateral cortical margin of the tibia; the dashed line denotes the peripheral margin of the lateral meniscus at midbody; the solid line with endpoints denotes measurement.

On the basis of an optimized testing protocol,[18] each knee was tested for anterior tibial translation (90 N) at 30°, 60°, and 90° of flexion and for pivot shift (7 N of valgus + 5 N of internal tibial torque) at full extension and 15° and 30° of flexion.[19] Specifically, the robotic testing system load cells (Omega 160 IP65; ATI) were calibrated using the gravity compensation and offset functions of the SimVitro software before each testing session. All testing was performed at room temperature, and specimens were kept hydrated with isotonic saline. For each knee status, the cadaveric knee was placed in full extension, and 30 N of compression (simulated weightbearing) load was delivered and verified such that no other forces or torques were noted, defining the neutral baseline position for each knee.[1,18]

As previously described, the robotic arm was used to execute a programmed protocol for each chosen flexion angle by delivering 90 N of anterior load with the 30-N compressive load maintained, allowing 30 seconds to stabilize to within ±0.5 N of the target load without restricting translation or rotation in any axis. Anterior translation (mm) of the tibia was captured and recorded using the SimVitro software after loading was achieved. Then, a portable ultrasound machine (GE LOGIQ E with 12L-RS 5-13 MHz Wideband Linear probe; GE Healthcare) was used to capture a longitudinal-axis (coronal cross-sectional) image of the midbody and posterior horn of the lateral meniscus. The peripheral edge of lateral meniscus and lateral cortical margin of the tibia were defined in each image, and the machine's calibrated measuring tool was used to determine meniscal extrusion based on offset (mm) of the edge of the meniscus relative to the proximolateral tibial cortex, which is accurate to ±0.2 mm (Figure 1).[2,7,12,18]

Pivot-shift testing was performed in a similar manner. The robotic arm was used to execute a programmed protocol for each flexion angle by delivering 5 N·m of internal rotation torque and 7 N·m of valgus torque with the 30-N compressive load maintained, allowing 30 seconds to stabilize to within ±0.5 N of target loads without restricting translation or rotation in any axis. Anterior translation (mm), internal rotation (degrees), and valgus angulation (degrees) of the tibia were captured and recorded using the SimVitro software after loading was achieved.[1,18,19] Then, lateral meniscal subluxation (cm) was determined as described above.

The robot arm was used to return the knee to its neutral baseline position after testing was completed. The specimen was detached from the robotic testing system with the memory-lock clamps remaining fixed in place on the femur and tibia to allow for precise remounting for subsequent testing of each status.

Surgical Procedures and Knee Status Testing Sequence

All operative procedures were performed arthroscopically to mimic the clinical situation by a board-certified sports medicine fellowship-trained orthopaedic surgeon with >30 years of experience (P.A.S.). The intact state was tested first, followed by ACL deficiency created via arthroscopic ACL transection; ACLR; LMORT 3 or 4 lesion; LMORT lesion repair; and finally, partial lateral meniscectomy. Using data for differences in anterior tibial translation from a previous study that reported clinically relevant changes of >5 mm,[18] a sample size of 8 per arm was determined to be sufficient for reaching the desired power of 0.8 with an alpha of .05. Specimens were randomly assigned to treatment (Figure 2).

ACL Reconstruction

An arthroscopic all-inside (retrograde drilling) ACLR procedure was performed using a 9.5 mm–diameter prepared quadrupled semitendinosus allograft (AlloSource). Graft lengths were 60 to 65 mm, and the 2 sutures in the tibial end of the graft were left intact. An adjustable-loop device (TightRope RT; Arthrex) was applied to the femoral end of the graft, and an adjustable-loop device with an attachable button (TightRope Attachable Button System [ABS]; Arthrex) was attached to the tibial end of the graft. Specimens tested with the native ACL were cut midsubstance, the central fibers were removed using a shaver, and the footprints were preserved for optimal ACLR socket placement. An outside-in femoral socket was created using a guide positioned from the anterolateral portal within the native ACL femoral footprint fibers with the knee at 90° of flexion while viewing medially. A retrograde reamer was drilled into the joint through a guide sleeve tapped 7 mm into the lateral femoral cortex. The retrograde reamer was opened to 9.5-mm diameter on the joint side to retrocut the femoral socket to a depth of 25 mm to allow for graft retensioning. The retrograde reamer was drilled back into the joint and retracted, and shuttle suture was passed through the guide sleeve into the joint and retrieved out of the lateral portal for later graft passage.

On the tibial side, a tibial aiming device was positioned within the native ACL footprint fibers, and with the knee

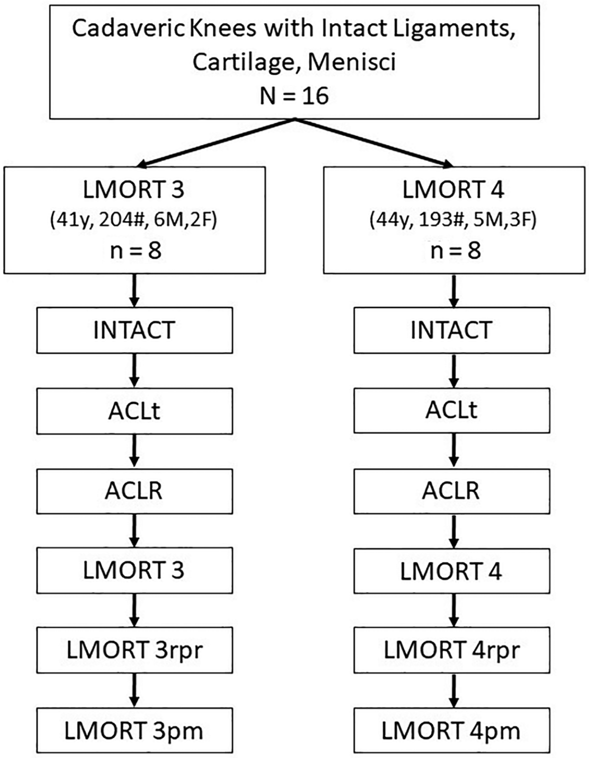

Figure 2. Order of testing sequences for each study arm. ACLR, anterior cruciate ligament reconstruction; ACLt, anterior cruciate ligament transection; F, female; LMORT, lateral meniscal oblique radial tear; M, male; pm, partial meniscectomy; rpr, repair. # means pounds.

flexed to ~75°, a 1.5-cm medial tibial incision was made for placement of the guide sleeve down to the bone. The retrograde reamer was then drilled into the joint and opened to 9.5-mm to then retrocut the tibial socket to a depth of 25 mm to allow room for graft retensioning. The retrograde reamer was brought back in the joint and retracted, passing a suture in the joint to serve as a shuttle. Both the femoral and the tibial shuttle sutures were retrieved out of the joint together via the anteromedial portal. The femoral shuttle suture was used to pull the femoral fixation button and its shortening strands across the joint, flipping the fixation button on the lateral femoral cortex. The graft was hoisted to a depth of 20 mm into the femoral socket via the shortening sutures. Next, the tibial end of the graft with its attached sutures and suspensory loop was shuttled into the tibial socket, delivering the loop and its shortening strands out of the tibial incision. An 11-mm rectangular button was applied to the ABS tibial suspensory loop, and the 2 sutures in the end of the graft were passed in the slits of the button. The knee was brought to full extension, and the tibial shortening strands were sequentially tightened. Then we placed the knee through 20 cycles of full knee motion including applying an anterior drawer, Lachman, and pivot-shift stress, and then the femoral shortening strands were tightened again in full extension.

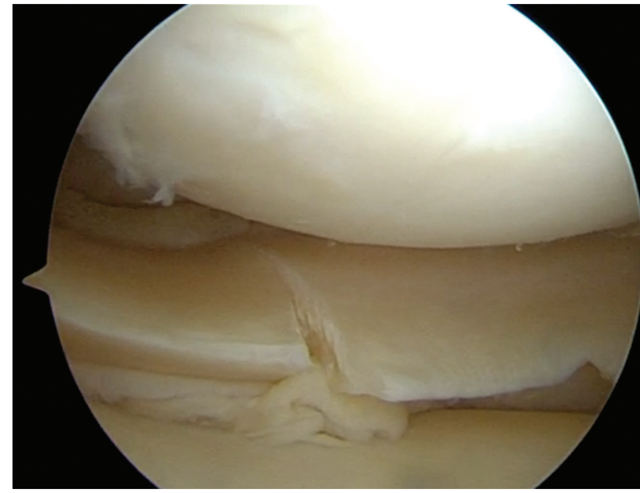

Figure 3. A lateral meniscal oblique radial tear type 3 (LMORT3) lesion created in a cadaveric left knee. The LMORT3 lesion is defined as an incomplete radial oblique posterior horn tear > 10 mm from the root and not extending to the capsule.

The tibial shortening strands were tightened once again with the knee in full extension to complete retensioning of the graft, and the 2 graft sutures were tied to the tibial button for additional fixation. Good graft position and tension were confirmed arthroscopically.

LMORT Lesion Creation and Repair

Based on the LMORT classification study, the 2 most common LMORT lesions seen in conjunction with ACL tears, LMORT 3 and 4, were evaluated.[11] Both lesions are located >1 cm from the lateral meniscus root, with the LMORT3 partial thickness not extending to the capsule and LMORT4 full thickness extending to the capsule. For the LMORT3 lesion, a measuring probe was placed 12 mm from the root attachment of the lateral meniscus, and arthroscopic scissors were used to make an oblique cut to within 3 mm of the meniscocapsular junction (Figure 3). The LMORT4 lesion was similarly made beginning 12 mm from the root and extending obliquely all the way through the meniscocapsular junction (Figure 4).

Arthroscopic repair of the LMORT 3 and 4 lesions was done similarly using a standard all-inside repair with 2 spanning horizontal mattress sutures. A cannula was placed in the lateral portal, and a suture passer (Knee Scorpion; Arthrex) was used to pass a 0.9-mm suture tape on each side of the tear nearest the capsule for a spanning suture. A locking, sliding Tuckahoe-type knot[21] was then tied followed by 2 alternating half-hitches utilizing a knot pusher. A second spanning suture was then placed more toward the free edge of the meniscus (Figure 5). Notably, none of the meniscal repairs failed after mechanical testing.

For partial meniscectomy of the LMORT 3 and 4 lesions, care was taken to only remove the unstable meniscal flap as would be done clinically, preserving as much meniscal

Figure 4. A lateral meniscal oblique radial tear type 4 (LMORT4) lesion created in a cadaveric left knee. The LMORT4 lesion is defined as a complete radial oblique posterior horn tear >10 mm from the root extending to the capsule.

rim as possible to ensure a balanced transition zone with the remaining meniscus (Figure 6).

Statistical Analysis

Mean ± standard deviation values and ranges were determined for each outcome measure at each knee status and flexion angle and for change (Δ) in each metric from the ACL-intact status. Changes (Δ) in anterior translation, internal rotation, and valgus displacements, as well as meniscal extrusion, from the intact state were measured and compared among all knee statuses for each cohort. One-way analysis of variance with Tukey post hoc test was used (SigmaStat 4.0; Systat) to compare raw data for statistically significant differences among each knee status for each knee flexion angle, with significance set at $P < .05$.

RESULTS

In both study arms, ACL transection was associated with significantly greater anterior translation compared with all other knee statuses for both anterior drawer and pivot-shift testing at all tested flexion angles ($P < .01$) (Figure 7). Notably, ACLR restored anterior translation comparable with the intact state at all angles of flexion for anterior drawer and pivot-shift testing. Valgus and internal rotation were not significantly affected for any knee status at any flexion angle ($p > .2$, post-hoc power < .74).

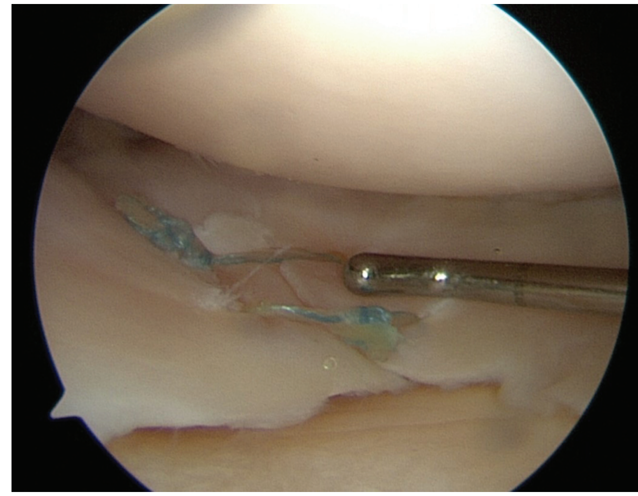

Figure 5. Lateral meniscal oblique radial tear type 3 (LMORT3) repair in a left knee. Both the LMORT 3 and lateral meniscal oblique radial tear type 4 lesions were repaired using 2 arthroscopically placed spanning horizontal mattress sutures to mimic what is done clinically.

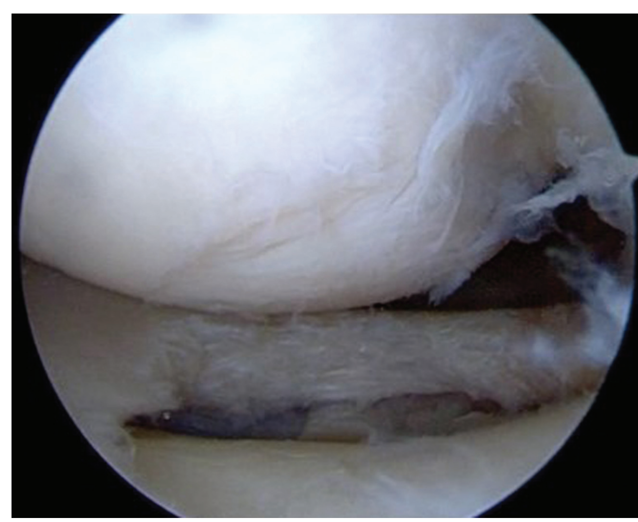

Figure 6. Partial lateral meniscectomy performed for a lateral meniscal oblique radial tear type 3 lesion in a right knee.

LMORT3 Lesions

For anterior drawer testing, ACLR + LMORT3 tear and ACLR + LMORT3 partial meniscectomy (pm) resulted in significantly greater anterior translation compared with ACL-intact knees at all flexion angles ($P < .05$) and compared with ACLR at 60° and 90° ($P < .014$). At 90° of flexion, anterior translation for ACL transection + LMORT3 pm was also significantly greater than for ACLR + LMORT3 repair ($P = .044$). Importantly, LMORT3 repair after ACLR restored anterior translation such that it was not significantly different compared with

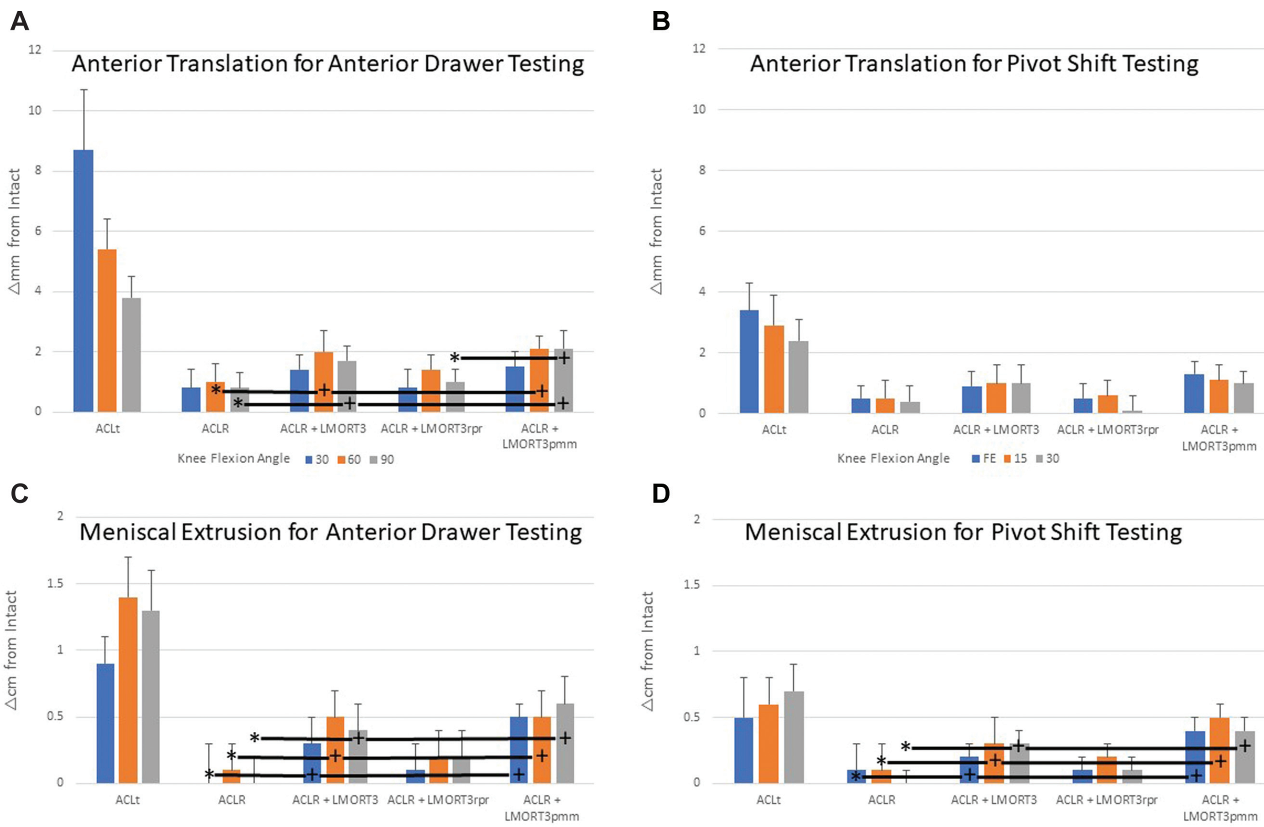

Figure 7. Mean ± SD values for (A, B) change (Δ) in anterior translation (mm) and (C, D) meniscal extrusion (cm) from intact for each status and flexion angle tested in anterior drawer (A, C) and pivot shift (B, D) to determine the biomechanical effects of lateral meniscal oblique radial tear type 3 (LMORT3) lesions and repairs in anterior cruciate ligament (ACL)–deficient and ACL-reconstructed cadaveric knees. + denotes statistically significant ($P < .05$) differences compared with * for LMORT treatment comparisons. ACLR, ACL reconstruction; ACLt, ACL transection; pm, partial menisectomy; FE, full extension; rpr, repair.

ACLR with the intact lateral meniscus for all flexion angles tested (Figure 7).

For pivot-shift testing, ACLR + LMORT3 tear was associated with significantly ($P = .041$) more anterior translation compared with intact knees at 15°. ACLR + LMORT3pm was associated with significantly more anterior translation compared with intact knees at full extension and 15° of flexion ($P < .03$). Importantly, LMORT3 repair after ACLR restored anterior translation such that it was not significantly different compared with ACLR with the intact lateral meniscus at full extension, 15°, and 30° (Figure 7).

Meniscal extrusion was significantly greater in ACL-transected knees compared with all other knee statuses for anterior drawer and pivot-shift testing at all testing angles ($P < .001$) (Figure 7; see Appendix Figure A1, available in the online version of this article). In addition, ACLR + LMORT3 tear and ACLR + LMORT3pm resulted in increased meniscal extrusion compared with intact knees and ACLR at all tested angles for anterior drawer and pivot shift ($P < .008$). Notably, there were no significant differences in meniscal extrusion between ACLR and ACLR + LMORT3 repair for anterior drawer or pivot-shift testing at all angles tested (Figure 7; Appendix Figure A1, available online).

LMORT4 Lesions

For anterior drawer testing, ACLR + LMORT4 tear and ACLR + LMORT4pm resulted in significantly greater anterior translation compared with intact knees and ACLR at all flexion angles tested ($P < .04$). Anterior translation after ACLR + LMORT4pm was significantly greater than after ACLR + LMORT4 repair ($P < .004$) at all flexion angles. ACLR + LMORT4 tear was associated with significantly ($P = .015$) more anterior translation than was ACLR + LMORT4 repair at 90°. LMORT4 repair after ACLR restored anterior translation to the level of ACLR with the intact lateral meniscus at all angles (Figure 8).

For pivot-shift testing, ACLR + LMORT4 tear and ACLR + LMORT4pm resulted in significantly ($P < .05$) more anterior translation than did all other statuses at all flexion angles tested. LMORT4 repair after ACLR restored anterior translation such that it was not significantly different from ACLR with the intact lateral meniscus at all flexion angles (Figure 8).

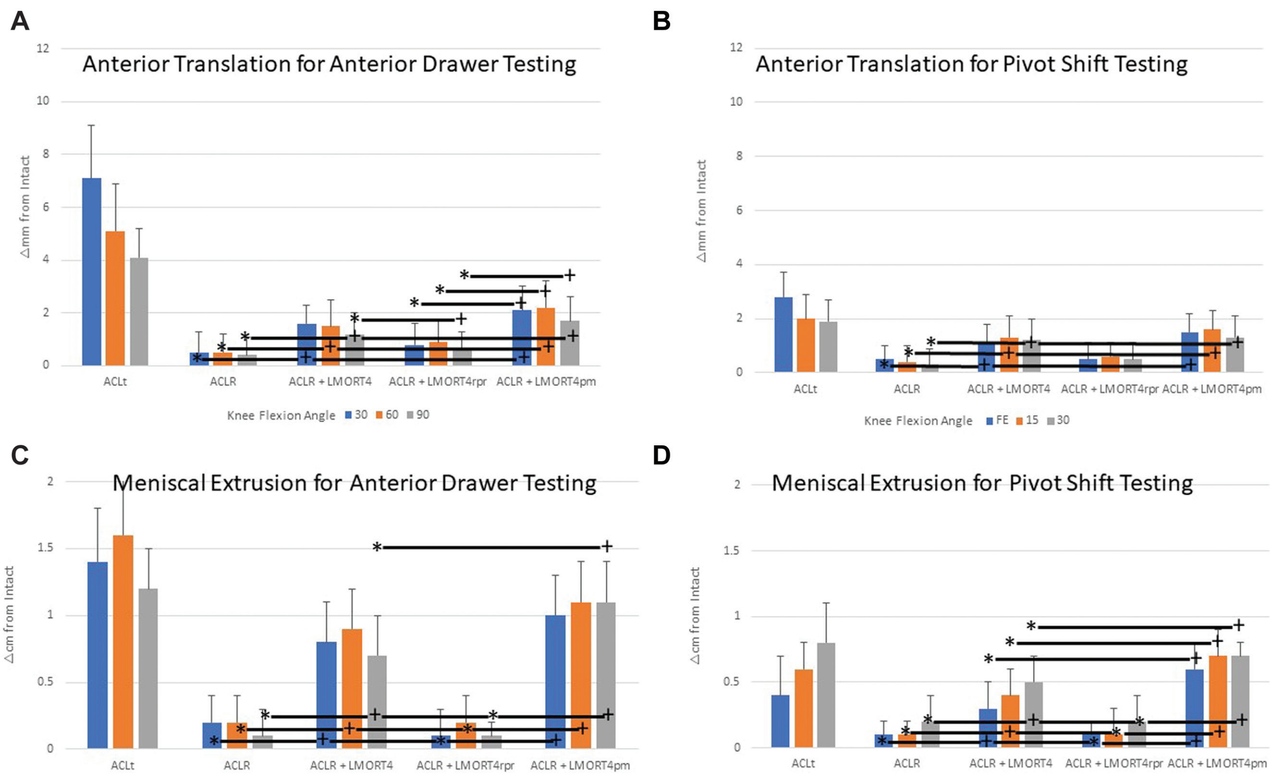

Figure 8. Mean ± SD values for (A, B) change (Δ) in anterior translation (mm) and (C, D) meniscal extrusion (cm) from intact for each status and flexion angle tested in anterior drawer (A, C) and pivot shift (B, D) to determine the biomechanical effects of lateral meniscal oblique radial tear type 4 (LMORT4) lesions and repairs and partial meniscectomy in anterior cruciate ligament (ACL)–reconstructed cadaveric knees. + denotes statistically significant ($P < .05$) differences compared with * for LMORT treatment comparisons. ACLR, ACL reconstruction; ACLt, ACL transection; FE, full extension; pm, partial meniscectomy; rpr, repair.

Meniscal extrusion was significantly greater in ACL-transected knees at all flexion angles tested when compared with all other knee statuses for anterior drawer and pivot-shift testing ($P < .04$) except for ACLR + LMORT4pm. For both anterior drawer and pivot-shift testing, ACLR + LMORT4 tear and ACLR + LMORT4pm resulted in increased meniscal extrusion compared with intact, ACLR, and ACLR + LMORT4 repair at all angles tested ($P < .05$). For anterior drawer testing at 90° of flexion and pivot-shift testing at all angles, meniscal extrusion after ACLR + LMORT4pm was significantly greater than after ACLR + LMORT4 tear ($P < .038$). There were no significant differences in meniscal extrusion between ACLR and ACLR + LMORT4 repair for anterior drawer or pivot-shift testing at all angles (Figure 8; Appendix Figure A1, available online).

The overall results are combined in Table 1 to highlight the kinematic and meniscal extrusion results for tested statuses for both LMORT 3 and 4 lesions.

DISCUSSION

The results of the present study allow the hypothesis to be accepted in that LMORT 3 and 4 lesions were associated with significantly increased anterior translation and lateral meniscal extrusion after ACLR, with arthroscopic repair restoring these kinematic parameters to intact levels, while partial meniscectomy further exacerbated the detrimental effects in the cadaveric model. These findings highlight the importance of LMORT 3 and 4 tears on joint stability and meniscal function such that these lesions should be considered to have clinical importance with respect to comprehensive management of the ACL-injured knee. Based on the significant differences with respect to the biomechanical effects of the lesion left untreated versus treated via repair or partial lateral meniscectomy as documented in the present study, arthroscopic side-to-side repair of LMORT 3 and 4 lesions should be performed in conjunction with ACLR whenever feasible.

A previous cadaveric biomechanical study verified the detrimental effects of LMORT 3 or 4 lesions on anterior instability and lateral meniscal extrusion in the presence of ACL deficiency.[18] Based on those findings, the present study was designed to investigate the clinical scenario regarding treatment of LMORT lesions in conjunction with ACLR. Best current evidence does not include validated recommendations to guide treatment decision making for either LMORT 3 or 4 lesions as to whether they should be left untreated, repaired, or removed via partial meniscectomy. Data from the present study delineate clinically relevant kinematic differences among these options. LMORT3 and, to an even greater degree, LMORT4 lesions were associated with significantly

TABLE 1
Summary of Major Kinematic Effects for LMORT Lesions and Repairs[a]

Test	Metric	ACLR + LMORT3 Tear	ACLR + LMORT3 Repair	ACLR + LMORT3 Partial Meniscectomy	ACLR + LMORT4 Tear	ACLR + LMORT4 Repair	ACLR + LMORT4 Partial Meniscectomy
Anterior drawer	Anterior translation	↑ Intact ↑ ACLR	= ACLR = Intact	↑ Intact ↑ ACLR $_{(60,90)}$ ↑ ACLR + LMORT3rpr $_{(90)}$	↑ Intact ↑ ACLR ↑ ACLR + LMORT4rpr	= ACLR = Intact	↑ Intact ↑ ACLR ↑ ACLR + LMORT4 ↑ ACLR + LMORT4rpr
	Meniscal extrusion	↑ Intact ↑ ACLR	= ACLR = Intact	↑ Intact ↑ ACLR	↑ Intact ↑ ACLR ↑ ACLR + LMORT4rpr	= ACLR = Intact	↑ Intact ↑ ACLR ↑ ACLR + LMORT4 ↑ ACLR + LMORT4rpr
Pivot shift	Anterior translation	↑ Intact $_{(15)}$	= ACLR = Intact	↑ Intact $_{(FE,15)}$	↑ Intact ↑ ACLR ↑ ACLR + LMORT4rpr	= ACLR = Intact	↑ Intact ↑ ACLR ↑ ACLR + LMORT4 ↑ ACLR + LMORT4rpr
	Meniscal extrusion	↑ Intact ↑ ACLR	= ACLR = Intact	↑ Intact ↑ ACLR	↑ Intact ↑ ACLR ↑ ACLR + LMORT4rpr	= ACLR = Intact	↑ Intact ↑ ACLR ↑ ACLR + LMORT4 ↑ ACLR + LMORT4rpr

[a]↑, significantly greater than; =, not significantly different; (n), specific knee flexion angle(s) for differences; ACLR, anterior cruciate ligament reconstruction; FE, full extension; LMORT3, lateral meniscal oblique radial tear type 3; LMORT4, lateral meniscal oblique radial tear type 4; rpr, repair.

increased anterior translation and meniscal extrusion compared with the ACL-intact condition and ACLR alone. Arthroscopic repair of LMORT 3 and 4 lesions restored measured kinematic parameters to ACL-intact levels. Partial meniscectomy did not improve measured kinematics for either type of LMORT and, in fact, exacerbated many of the detrimental effects measured in the present study.

While previous studies have suggested that leaving some lateral meniscal tears in the ACL-injured knee untreated can be associated with low reoperation rates after ACLR,[3,17] meniscal healing, function, and related symptoms and progression of osteoarthritis are unaccounted for by this metric. In fact, a study that included second-look arthroscopy to evaluate meniscal tears that were left untreated at the time of ACLR found only 74% of lateral meniscal tears to be healed while 7% of these tears propagated.[22] Furthermore, a recent biomechanical study designed to simulate a cutting maneuver in cadaveric knees demonstrated that 10-mm longitudinal posterior horn tears propagated in 28.7% of intact and 26.1% of ACL-deficient knees, respectively.[15] The same study showed that external tibial rotation significantly increased by up to 45.5%, with meniscal tear propagation at all flexion angles, even in intact knees. Similarly, biomechanical and clinical data have strongly suggested that partial lateral meniscectomy is associated with kinematic, functional, and clinical perturbations that can have severe consequences on joint health.[4,16] The data from the present study provide evidence that leaving LMORT 3 or 4 lesions untreated or treating them with partial lateral meniscectomy may have similar consequences on the ACL-reconstructed knee.

In terms of the meniscal repair procedure chosen for this study, we elected to use a clinically relevant and reproducible arthroscopic technique with 2 all-inside horizontal mattress spanning sutures. Normal meniscal contour and mobility were restored while avoiding potential overconstraint from suturing directly to the capsule or via a transtibial approach. Notably, ultrasonographic assessments confirmed correction of meniscal extrusion after repair of both LMORT 3 and LMORT4 lesions. While a recent study reported biomechanical advantages associated with the use of modified "cross" tie-grip sutures for repair of radial meniscal tears,[13] arthroscopic use of this suture pattern is only feasible in the midportion of the meniscus. Therefore, the modified cross tie-grip technique does not apply to LMORT repair. Importantly, none of the suture repairs of LMORT 3 or 4 lesions performed in the present study failed throughout multiphase biomechanical testing. In addition, Tsujii et al[20] reported 3-year clinical outcomes after side-to-side repairs for posterior horn radial/flap tears of the lateral meniscus in conjunction with ACLR, demonstrating a healing rate of 90% based on clinical, arthroscopic, and radiographic outcome measures.

Limitations of the present study include its time-zero biomechanical experimental design, which does not account for associated capsular or ligamentous injuries. Perhaps more importantly, the design limits the conclusions to be valid only under the assumption that the ACLR and meniscal repairs would consistently result in functional healing. Further, neither maximal-activity loading nor extended cyclical loading testing was performed, and differences in rotational and valgus translations did not reach statistical significance or post hoc power >0.8. As such, the study may have been underpowered with respect to its secondary outcome measures. Therefore, the results of the present study should be interpreted and applied as preclinical ex vivo data from standardized biomechanical testing of younger normal cadaveric knees. In addition, the use of sectioned cadaveric knee–only specimens did not allow for clinically relevant measurement of individual anatomic characteristics, including tibial slope, based on a diagnostic imaging of the full lower extremity. However, specimens were randomized to treatment cohorts, and measurements were calculated and analyzed based on change in value from baseline (intact status) to control for these potential confounding variables by using within-knee differences for comparisons.

The data from the present study confirmed that LMORT 3 and 4 lesions accentuate anterior drawer and pivot-shift laxity, as well as meniscal extrusion, after ACLR in the cadaveric model. Arthroscopic side-to-side repair of LMORT lesions effectively restored normal measured knee kinematics. Partial meniscectomies for LMORT 3 and 4 tears were associated with greater anterior translation, pivot shift, and meniscal extrusion, even after effective ACLR. These ex vivo data have important clinical relevance in that LMORT lesions are common in conjunction with ACL tears and adversely affect joint stability and meniscal extrusion.

ORCID iD

Aaron J. Krych https://orcid.org/0000-0003-3248-8007

REFERENCES

1. Colbrunn RW, Dumpe JE, Nagle TF, Kolmodin JD, Barsoum WK, Saluan PM. Robotically simulated pivot shift that represents the clinical exam. *J Orthop Res*. 2019;37(12):2601-2608. doi:10.1002/jor.24439
2. Cook JL, Cook CR, Stannard JP, et al. MRI versus ultrasonography to assess meniscal abnormalities in acute knees. *J Knee Surg*. 2014;27(4):319-324. doi:10.1055/s-0034-1367731
3. Duchman KR, Westermann RW, Spindler KP, et al. The fate of meniscus tears left in situ at the time of anterior cruciate ligament reconstruction: a 6-year follow-up study from the MOON Cohort. *Am J Sports Med*. 2015;43(11):2688-2695. doi:10.1177/036354651 5604622
4. Feeley BT, Lau BC. Biomechanics and clinical outcomes of partial meniscectomy. *J Am Acad Orthop Surg*. 2018;26(24):853-863. doi:10.5435/JAAOS-D-17-00256
5. Feucht MJ, Salzmann GM, Bode G, et al. Posterior root tears of the lateral meniscus. *Knee Surg Sports Traumatol Arthrosc*. 2015; 23(1):119-125. doi:10.1007/s00167-014-2904-x
6. Frank JM, Moatshe G, Brady AW, et al. Lateral meniscus posterior root and meniscofemoral ligaments as stabilizing structures in the ACL-deficient knee: a biomechanical study. *Orthop J Sports Med*. 2017;5(6):2325967117695756. doi:10.1177/2325967117695756
7. GE Healthcare. Technical Publications Direction 5314626-100 Rev 3. Accessed May 19, 2022. https://www.bioclinicalservices.com.au/ge-healthcare/logiq-ultrasound-systems/logiq-e-user-guide-rev-3
8. Goldsmith MT, Smith SD, Jansson KS, LaPrade RF, Wijdicks CA. Characterization of robotic system passive path repeatability during specimen removal and reinstallation for in vitro knee joint testing. *Med Eng Phys*. 2014;36(10):1331-1337. doi:10.1016/j.medengphy .2014.06.022
9. Hoshino Y, Hiroshima Y, Miyaji N, et al. Unrepaired lateral meniscus tears lead to remaining pivot-shift in ACL-reconstructed knees. *Knee Surg Sports Traumatol Arthrosc*. 2020;28(11):3504-3510. doi:10.10 07/s00167-020-06007-3
10. Hoshino Y, Miyaji N, Nishida K, et al. The concomitant lateral meniscus injury increased the pivot shift in the anterior cruciate ligament-injured knee. *Knee Surg Sports Traumatol Arthrosc*. 2019;27(2): 646-651. doi:10.1007/s00167-018-5209-7
11. Krych AJ, LaPrade MD, Cook CS, et al. Lateral meniscal oblique radial tears are common with ACL injury: a classification system based on arthroscopic tear patterns in 600 consecutive patients. *Orthop J Sports Med*. 2020;8(5):2325967120921737. doi:10.1177/ 2325967120921737
12. Mahn MM, Cook JL, Cook CR, Balke MT. Arthroscopic verification of ultrasonographic diagnosis of meniscal pathology in dogs. *Vet Surg*. 2005;34(4):318-323. doi:10.1111/j.1532-950X.2005.00049.x
13. Matsubara H, Okazaki K, Izawa T, et al. New suture method for radial tears of the meniscus: biomechanical analysis of cross-suture and double horizontal suture techniques using cyclic load testing. *Am J Sports Med*. 2012;40(2):414-418. doi:10.1177/0363546511424395
14. Musahl V, Citak M, O'Loughlin PF, Choi D, Bedi A, Pearle AD. The effect of medial versus lateral meniscectomy on the stability of the anterior cruciate ligament-deficient knee. *Am J Sports Med*. 2010;38(8):1591-1597. doi:10.1177/0363546510364402
15. Novaretti JV, Herbst E, Chan CK, Debski RE, Musahl V. Small lateral meniscus tears propagate over time in ACL intact and deficient knees. *Knee Surg Sports Traumatol Arthrosc*. 2021;29(9):3068-3076. doi:10.1007/s00167-020-06356-z
16. Novaretti JV, Lian J, Patel NK, et al. Partial lateral meniscectomy affects knee stability even in anterior cruciate ligament-intact knees. *J Bone Joint Surg Am*. 2020;102(7):567-573. doi:10.2106/JBJS.19 .00712
17. Shelbourne KD, Heinrich J. The long-term evaluation of lateral meniscus tears left in situ at the time of anterior cruciate ligament reconstruction. *Arthroscopy*. 2004;20(4):346-351. doi:10.1016/j.arthro .2004.01.029
18. Smith PA, Bezold WA, Cook CR, et al. Kinematic analysis of lateral meniscal oblique radial tears in the anterior cruciate ligament–deficient knee. *Am J Sports Med*. 2021;49(14):3898-3905. doi:10.1177/ 03635465211052521
19. Tang X, Marshall B, Wang JH, et al. Lateral meniscal posterior root repair with anterior cruciate ligament reconstruction better restores knee stability. *Am J Sports Med*. 2019;47(1):59-65. doi:10.1177/ 0363546518808004
20. Tsujii A, Yonetani Y, Kinugasa K, et al. Outcomes more than 2 years after meniscal repair for longitudinal tears of the lateral meniscus combined with anterior cruciate ligament reconstruction. *Am J Sports Med*. 2021;49(3):684-692. doi:10.1177/0363546520981976
21. Wiley WB, Goradia VK. The Tuckahoe knot: a secure locking slip knot. *Arthroscopy*. 2004;20(5):556-559. doi:10.1016/j.arthro.2004 .01.035
22. Yagishita K, Muneta T, Ogiuchi T, Sekiya I, Shinomiya K. Healing potential of meniscal tears without repair in knees with anterior cruciate ligament reconstruction. *Am J Sports Med*. 2004;32(8):1953-1961. doi:10.1177/0363546504263702