Concomitant Meniscotibial Ligament Reconstruction Decreases Meniscal Extrusion Following Medial Meniscus Allograft Transplantation: A Cadaveric Analysis

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Purpose: To compare meniscal extrusion (ME) following medial meniscus allograft transplantation (MMAT) with and without meniscotibial ligament reconstruction (MTLR). **Methods:** Ten cadaveric knees were size-matched with meniscus allografts. MMAT was performed via bridge-in-slot technique. Specimens were mounted in a testing system and ME was assessed via ultrasound anterior, directly over, and posterior to the medial collateral ligament at the joint line under 4 testing conditions: (1) 0° flexion and 0 newtons (N) of axial load, (2) 0° and 1,000 N, (3) 30° and 0 N, and (4) 30° and 1,000 N. For each condition, "mean total extrusion" was calculated by averaging measurements at each position. Next, MTLR was performed using 2 inside-out sutures through the remnant allograft meniscotibial ligament and secured to the tibia using anchors. The testing protocol was repeated. Differences in ME between MMAT alone versus MMAT + MTLR were examined. Within-group differences between the measurement positions, loading states, and flexion angles also were assessed. **Results:** "Mean total extrusion" was greater following MMAT alone (2.56 ± 1.23 mm) versus MMAT + MTLR (2.14 ± 1.07 mm; $P = .005$) in the loaded state at 0° flexion. ME directly over the MCL was greater following MMAT alone (3.51 ± 1.00 mm) compared with MMAT + MTLR (2.93 ± 0.79 mm; $P = .054$). Posteriorly, in the loaded state at 0°, ME was greater following MMAT alone (2.43 ± 1.10 mm) compared with MMAT + MTLR (1.96 ± 0.99 mm; $P = .010$). In all conditions, ME was greater in the loaded state versus the unloaded state. **Conclusions:** Following MMAT, the addition of MTLR significantly reduced overall ME when compared with isolated MMAT during loading at 0° of flexion in a cadaveric model; given the small absolute values of change in extrusion, clinical significance cannot be gleaned from these findings. **Clinical Relevance:** During medial meniscus allograft transplantation, augmentation with meniscotibial ligament reconstruction may limit meniscal extrusion and improve the biomechanical milieu of the knee joint following transplant.

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Meniscal deficiency has a detrimental effect on knee joint mechanics, accelerating the progression of tibiofemoral osteoarthritis (OA) and causing debilitating knee pain and functional impairment.[1-5] Meniscus allograft transplantation (MAT) is a viable treatment option in the setting of meniscal deficiency.[6] Despite favorable clinical outcomes with relatively low failure rates at mid- to long-term follow-up, several studies have reported continued progression of OA despite transplantation.[7-10] Medial meniscus allograft transplantation (MMAT), in particular, has been associated with greater progression of OA,[11] whereas meniscal graft extrusion, reported to occur in up to 61% of patients undergoing MAT, remains a concern.[12-14] While the clinical significance of allograft extrusion is equivocal,[15,16] it has been shown that meniscal extrusion (ME) following MAT diminishes the biomechanically protective effects of the meniscal graft, increasing mechanical wear and chondral degeneration.[17-19]

Several MAT techniques, including open and arthroscopically assisted, have been described. Three common modalities for allograft root fixation include arthroscopic soft tissue, bone plugs, and the bridge-in-slot technique.[20] While the ideal root fixation technique remains controversial,[21] augmentation techniques incorporating peripheral bony fixation to minimize ME have gained increasing interest, with several basic-science and clinical investigations having been conducted.[22-29] Given that the anatomical role of the meniscotibial ligament (MTL) is to constrain against medial ME,[30] along with reports that MTL repair reduces extrusion in a native meniscus model,[31] an MMAT technique that incorporates reconstruction of the MTL (MTLR) represents a promising option for addressing post-MMAT extrusion.

The purpose of this investigation was to compare ME following MMAT with and without MTLR. We hypothesized that the addition of MTLR during MMAT would reduce ultrasound-measured ME when compared with MMAT alone.

Methods

Ten (3 male, 7 female) fresh-frozen human cadaveric knees were obtained from 6 donors (MedCure, Portland, OR) with no history of previous knee surgery. Mean cadaver age was 53.8 (standard deviation 4.26) years with a mean body mass index of 25.4 (standard deviation 4.24). Knee specimens were radiographed with a calibrating ball to allow for meniscal allograft sizing, which was performed using the Pollard method.[32] Size-matched fresh-frozen meniscal allografts were obtained for each specimen (JRF Ortho, Centennial, CO). Allograft menisci were obtained as whole tibial plateaus with a "skirt" of the medial MTL left intact (Fig 1). Typically, this "skirt" is trimmed in the preparation process before shipment for clinical use.

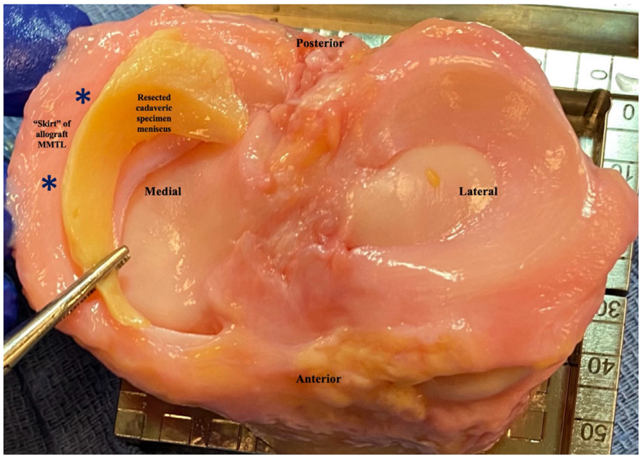

Fig 1. Allograft meniscus before preparation in a left knee. The medial meniscus, resected en-bloc from the cadaveric testing specimen, is held over the allograft medial meniscus to demonstrate appropriate graft sizing. The "skirt" of excess tissue around the periphery of the allograft is the remnant medial meniscotibial ligament (MMTL). Once the allograft was prepared and passed into the cadaveric joint for standard bridge-in-slot meniscus allograft transplantation, 2 separate meniscal repair sutures were passed in horizontal mattress configuration at the locations of the asterisks and secured to the cadaveric proximal tibia with suture anchors to create the meniscotibial ligament reconstruction.

Specimens were prepared by cutting the tibial diaphysis 30 cm from the joint line and the femoral diaphysis 20 cm from the joint line. All soft tissues proximally and distally to a point 10 cm from the joint line were removed (Fig 2). The exposed femur and tibia were then potted in 10 cm-diameter polyvinyl chloride tubing (10 cm in length for the tibial side, 7.6 cm for the femoral side) using a dental acrylic (Isocryl; Lange Dental, Wheeling, IL). Screws were placed through the polyvinyl chloride tubing, epoxy resin, and shaft of each long bone to provide further stability to withstand loads during testing procedures.

Surgical Technique

All surgical steps were performed by a fellowship-trained orthopaedic sports medicine surgeon (D.M.K.). A modified version of a previously described bridge-in-slot MAT technique was performed.[33] While the described technique relies on arthroscopic total meniscectomy of the native meniscus, a mini-open approach created through a medial parapatellar arthrotomy incision was used to resect the native meniscus en-bloc using an 11-blade scalpel (Fig 1). This was performed to verify appropriate soft-tissue sizing during allograft trimming and preparation. Following meniscectomy, the tibial slot was created using a combination of arthroscopic shaver and reamer

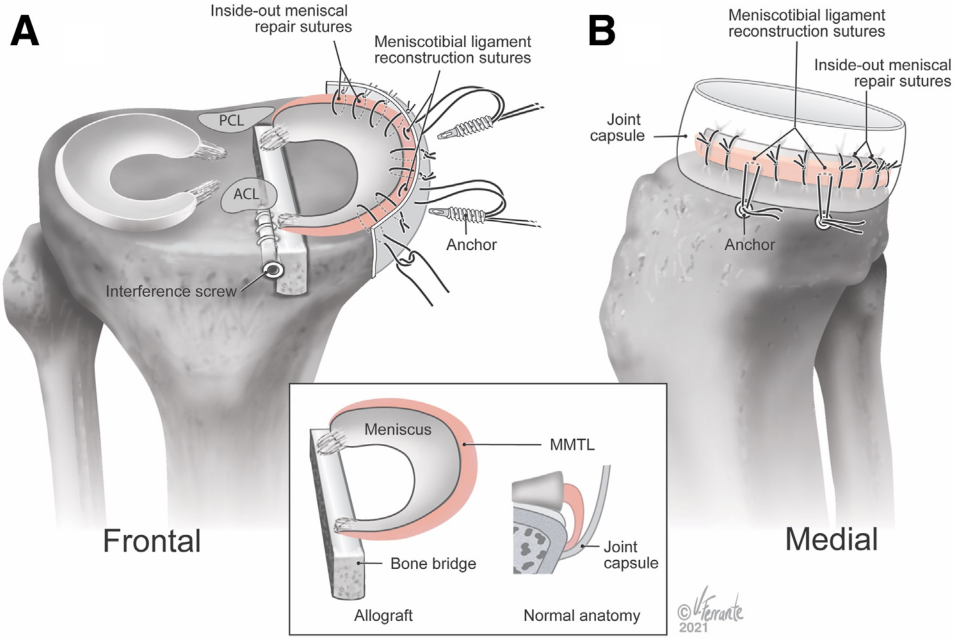

Fig 2. Illustration of bridge-in-slot meniscus allograft transplantation with concomitant meniscotibial ligament reconstruction in a right knee. (A) Frontal view of the proximal tibia showing the meniscus allograft secured in place via the bone bridge and interference screw with peripheral inside-out repair sutures. The additional medial meniscotibial ligament (MMTL) reconstruction is performed with 2 additional inside-out repair sutures attached to anchors that are placed in the tibial cortex. (B) Medial view of the proximal tibia showing the final MMTL reconstruction configuration with anchors in place in the proximal tibia.

from anterior-to-posterior in line with the native meniscal roots. Care was taken to leave the posterior tibial cortex intact. The pilot slot was rasped to a depth of 10 mm × 8 mm width. Concurrently, the allograft meniscus was prepared using a saw, leaving a bridge of bone connecting the roots. This bridge was sized to match the slot. Using the resected native meniscus as a guide, the “skirt” of allograft MTL was trimmed to allow for passage of meniscal repair sutures along its periphery. A standard posteromedial incision, with dissection down to the posteromedial joint capsule, was created to facilitate inside-out repair following insertion of the allograft.[31]

A single 0-PDS suture (Ethicon, Blue Ash, OH) was placed in a vertical mattress fashion through the junction of the middle and posterior third of the allograft to

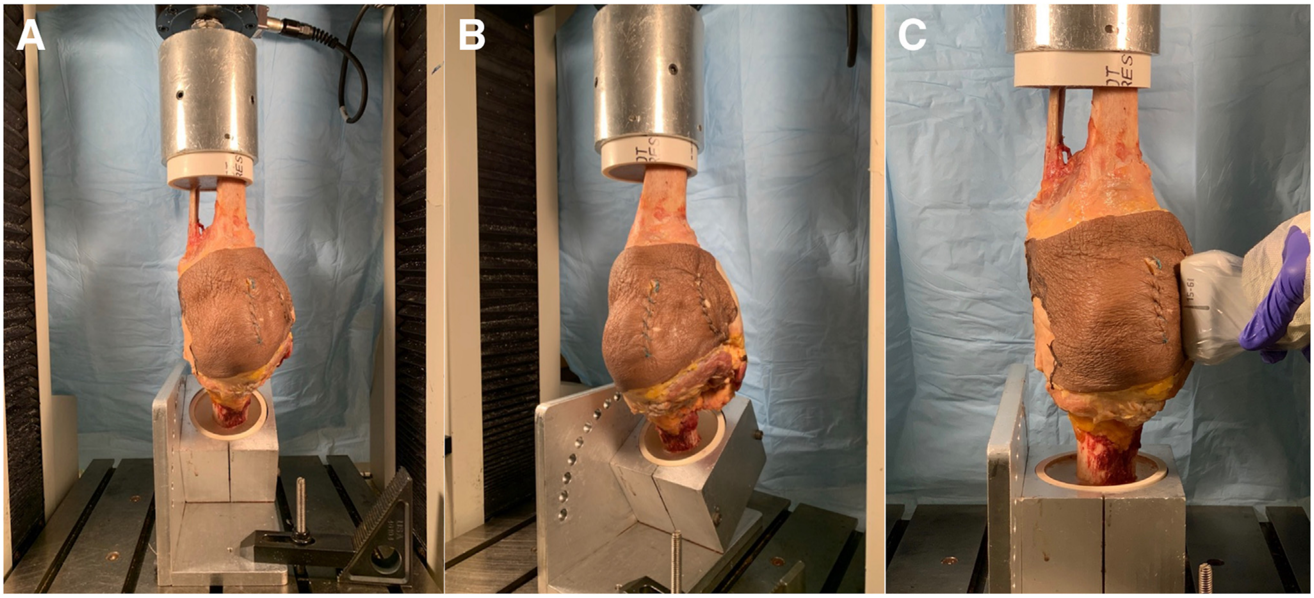

Fig 3. A prepared cadaveric left knee specimen potted with epoxy-resin cement in polyvinyl chloride tubes, loaded upside-down in a materials testing system (Insight 5; MTS Systems Corp., Eden Prairie, MN). (A) Anterior view with the knee locked in 30° flexion via an adjustable jig. (B) Oblique view with the knee locked in 30° flexion via the adjustable jig. (C) Anterior view with the knee locked in 0° flexion via the adjustable jig. A linear ultrasound probe is held against the medial joint line for examination of medial meniscus extrusion.

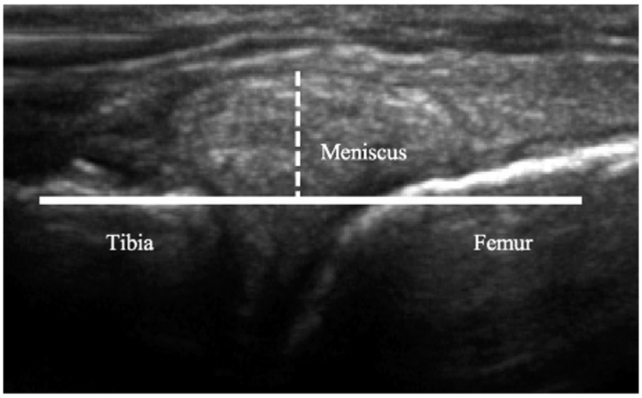

Fig 4. Ultrasound image of an extruded medial meniscus in a right knee. The solid white line represents the edge of the joint line, and the dotted line represents a measurement to the point of maximum meniscal extrusion perpendicular to the edge of the joint line. The tibia, femur, and meniscus are labeled.

serve as a traction stitch. The allograft was introduced into the knee using the traction stitch and the bone bridge was secured in the slot with a 5.5- × 19.1-mm bioabsorbable interference screw (Arthrex, Naples, FL). Ten meniscal repair sutures (2-0 FiberWire; Arthrex) were then passed one-by-one along the meniscal body in vertical mattress formation using an inside-out technique. Sutures were secured to the joint capsule using alternating half-hitches. Incisions were closed in a simple running fashion and the specimen was transported to the testing apparatus.

Following extrusion measurements, the specimen was returned to the surgical station for MTLR. The incisions were re-opened and two additional meniscal repair sutures (2-0 FiberWire; Arthrex) were placed in horizontal mattress formation through the remnant allograft MTL "skirt" using an inside-out technique. One suture was placed at the transition point of the anterior horn and mid-body while the other was placed at the transition point of the posterior horn and mid-body (Fig 2), these 2 suture placements are similar to those described by Debieux et al. in their meniscus centralization technique.[19] After retrieval from the posteromedial incision, these sutures were threaded through 2 respective 3.5-mm anchors (SwiveLock; Arthrex), which were inserted into the medial cortex of the proximal tibia under suitable tension. The incisions were closed and the specimen returned to the loading apparatus for final testing and measurements.

Loading Protocol

A materials testing system (Insight 5; MTS Systems Corp., Eden Prairie, MN) was used to place the specimen under a direct axial compression load. First, the specimen was fitted in the testing system using a custom jig that could be locked at various angles (Fig 3A). Specimens were loaded in an inverted fashion to ensure ground forces acted perpendicular to the plane of the tibial plateau when testing the flexed condition (Fig 3 B and C). The 0° (i.e., full extension) condition was tested first. ME was measured with an ultrasound probe first under zero newtons (N) of axial force and then under 1,000 N. We selected 1,000 N based on previous data reported by Daney et al.[34] The 1,000-N axial compression force was steadily applied while ultrasound images were captured at each imaging position (anterior, middle, posterior). The specimen was then adjusted in the jig and locked in 30° of knee flexion and the same loading and ultrasound image

Table 1. Between-Group Comparisons of Meniscal Extrusion

Measurement Position	Testing Parameters	MMAT Alone, Extrusion in mm, Average (SD)	MMAT Plus MTLR, Extrusion in mm, Average (SD)	*P* Value	95% Confidence Interval [Lower Bound, Upper Bound]
Anterior	0°, 0 N	1.25 (1.46)	1.27 (1.29)	.930	[−0.56, 0.52]
	30°, 0 N	0.65 (1.06)	0.53 (0.90)	.704	[−0.57, 0.81]
	0°, 1000 N	1.99 (1.20)	1.70 (1.10)	.390	[−0.44, 1.02]
	30°, 1000 N	0.87 (1.06)	0.72 (1.10)	.636	[−0.54, 0.84]
Middle	0°, 0 N	3.23 (1.04)	2.57 (0.91)	.062	[−0.04, 1.36]
	30°, 0 N	1.40 (0.89)	1.41 (1.19)	.944	[−0.49, 0.46]
	0°, 1000 N	3.51 (1.00)	2.93 (0.79)	.054	[−0.01, 1.18]
	30°, 1000 N	2.26 (0.81)	1.89 (1.29)	.366	[−0.56, 1.30]
Posterior	0°, 0 N	1.41 (1.31)	1.35 (1.25)	.752	[−0.36, 0.48]
	30°, 0 N	1.87 (1.18)	2.10 (1.05)	.671	[−0.80, 0.34]
	0°, 1000 N	2.43 (1.10)	1.96 (0.99)	**.010**	[0.14, 0.80]
	30°, 1000 N	3.10 (1.51)	2.97 (1.65)	.437	[−0.23, 0.49]
"Total extrusion"	0°, 0 N	1.82 (1.52)	1.64 (1.28)	.197	[−0.10, 0.47]
	30°, 0 N	1.30 (1.16)	1.34 (1.21)	.636	[−0.36, 0.27]
	0°, 1000 N	2.55 (1.23)	2.11 (1.07)	**.005**	[0.14, 0.72]
	30°, 1000 N	2.06 (1.52)	1.86 (1.65)	.211	[−0.12, 0.52]

P values in bold represent statistical significance ($P < .05$).

MMAT, medial meniscus allograft transplantation; MTLR, meniscotibial ligament reconstruction; N, newtons; SD, standard deviation.

acquisition protocol was performed. Flexion angles of 0° and 30° were selected to approximate typical joint angles during walking and based on the angles tested in a similar study by Hewison et al.[22]

Ultrasound Extrusion Measurement

A fellowship-trained orthopaedic sports medicine surgeon (D.M.K.) performed all ultrasound assessments after a training session with a fellowship-trained musculoskeletal radiologist. A linear ultrasound probe (M-Turbo; HFL50X Sonosite, Bothell, WA) set to a standardized depth of 2.5 cm[31] was held against the skin along the medial tibiofemoral joint line and ultrasound images were captured at 3 separate locations from anterior to posterior. Images were captured anterior to the medial collateral ligament (MCL) at the level of the medial joint line ("anterior"), over the MCL ("middle"), and then posterior to the MCL ("posterior"). This procedure was performed under 4 conditions: (1) 0° of knee flexion and 0 N of axial load, (2) 0° of knee flexion and 1,000 N of axial load, (3) 30° of knee flexion and 0 N of axial load, and (4) 30° of knee flexion and 1,000 N of axial load. This testing procedure was first performed following isolated MMAT (control condition) and then following MTLR augmentation (experimental condition). Baseline native meniscus extrusion measures were omitted, in line with other studies investigating differences in extrusion for various MAT fixation techniques.[22,24,25,29] All captured ultrasound images were loaded into ImageJ software (U.S. National Institutes of Health, Bethesda, MD), which was used to measure ME according to the methods described by Özdemir et al. (2019).[35] In summary, ME was quantified as the perpendicular linear distance between the peripheral edge of the meniscus and a line connecting the cortices of the proximal tibial plateau and the distal medial femoral condyle (Fig 4). Measurements were performed in triplicate for all images, and an average of the 3 measurements was used in statistical analysis.

Statistical Analysis

Sample size was calculated based on previously published data regarding ultrasonographic measurement of medial ME with and without MTLR.[31] It was determined that 10 specimens were required to obtain 80% power to detect a significant difference in ME between the MMAT alone and MMAT + MTLR with an alpha level of .05. Descriptive analyses of the data are presented with means and standard deviations. Intrarater reliability of extrusion measurements was assessed via the intraclass correlation coefficient.

Normality of continuous measures was assessed via the Shapiro—Wilk test. Extrusion measurements were compared following isolated MMAT versus MMAT + MTLR using paired *t*-tests for normally distributed data and Wilcoxon signed-rank tests for non-normally distributed data. Between-group comparisons were made for each measurement position ("anterior," "middle," and "posterior") and for a "mean total extrusion" measure that was calculated by averaging values from all 3 positions. A 3-way mixed analysis of variance was used to determine if there was an interaction between fixation technique following MMAT +/− MTLR, loading state, and flexion angle for the mean total extrusion measure.

Within-group differences in ME between flexion angles (0° vs 30°) and loading states (0 N vs 1000 N) were assessed with paired *t*-tests (normally distributed data) and Wilcoxon signed-rank tests (non-normally distributed data). Differences in ME between the 3 measurement positions were assessed using one-way analysis of

Table 2. Within-Group Significance Testing of Multiple Comparisons: Anterior Versus Middle Versus Posterior Position Extrusion Measurements (*P* Values Only; Refer to Table 1 for Actual Extrusion Values)

	MMAT Alone		MMAT Plus MTLR	
Testing Parameters	3-Way *P* Value (Anterior vs Middle vs Posterior)	Significant Post-Hoc Pairwise Comparisons	3-Way *P* Value (Anterior vs. Middle vs Posterior)	Significant Post-Hoc Pairwise Comparisons
0°, 0 N	**.001**	Anterior vs middle (*P* = **.023**; 95% CI [−3.84, −0.90]); middle vs posterior (*P* = **.006**; 95% CI [1.06, 2.97])	**.007**	Anterior vs. middle (*P* = **.027**; 95% CI [−2.86, −0.62])
0°, 1000 N	**.042**	Anterior vs middle (*P* = **.023**; 95% CI [−3.09, −0.28])	**.009**	Anterior vs. middle (*P* = **.042**; 95% CI [−2.72, −0.45])
30°, 0 N	.123	−	**.008**	Anterior vs. Posterior (*P* = **.006**; 95% CI [−2.34, −0.80])
30°, 1000 N	**.003**	Anterior vs. middle (*P* = **.026**; 95% CI [−3.07, −0.67]); anterior vs. posterior (*P* = **.016**; 95% CI [−3.20, −1.26])	**.012**	Anterior vs. Posterior (*P* = **.022**; 95% CI [−3.39, −1.11)

P values in bold represent statistical significance ($P < .05$).

CI, confidence interval; MMAT, medial meniscus allograft transplantation; MTLR, meniscotibial ligament reconstruction; N, newtons; SD, standard deviation.

Table 3. Within-Group Significance Testing of 0-N Versus 1,000-N Axial Load (*P* Values Only; Refer to Table 1 for Actual Extrusion Values)

	Testing Parameters	*P* Value of 0 N vs 1,000 N	95% Confidence Interval [Lower Bound, Upper Bound]
MMAT alone	0°, anterior	.088	[−0.14, 1.62]
	0°, middle	**.047**	[0.01, 0.57]
	0°, posterior	**.002**	[0.48, 1.56]
	0°, "total extrusion"	**<.001**	[0.37, 1.08]
	30°, anterior	.311	[−0.24, 0.68]
	30°, middle	**.022**	[0.18, 1.54]
	30°, posterior	**.012**	[0.35, 2.11]
	30°, "total extrusion"	**<.001**	[0.36, 1.15]
MMAT plus MTLR	0°, anterior	**.040**	[0.02, 0.84]
	0°, middle	.276	[−0.37, 1.09]
	0°, posterior	**.018**	[0.13, 1.09]
	0°, "total extrusion"	**<.001**	[0.22, 0.73]
	30°, anterior	.067	[−0.02, 0.40]
	30°, middle	.066	[−0.04, 0.99]
	30°, posterior	**.006**	[0.32, 1.42]
	30°, "total extrusion"	**<.001**	[0.27, 0.76]

P values in bold represent statistical significance ($P < .05$).
MMAT, medial meniscus allograft transplantation; MTLR, meniscotibial ligament reconstruction; N, newtons.

variance (normally distributed data) and Friedman's test (non-normally distributed data). All tests were 2-tailed and statistical significance was set at $P < .05$. Analyses were performed using SPPS, version 27 (IBM Corp., Armonk, NY).

Results

The intraclass correlation coefficient for intrarater reliability of triplicate ME measurements was 0.960, 95% confidence interval (CI) 0.952-0.967; $P <.001$. Mean total extrusion was significantly greater following isolated MMAT (2.56 ± 1.23 mm) compared with MMAT + MTLR (2.14 ± 1.07 mm; $P = .005$; 95% CI 0.14-0.72) in the loaded state at 0° of flexion. No significant differences in mean total extrusion were found at other loading states and flexion angles (Table 1). When considering the relationship of fixation technique, loading state, and flexion angle, no significant 3-way interaction was found based on mean total extrusion measurements ($P = .771$).

At the "middle" position, in the loaded state at 0° of flexion, the difference between MMAT alone (3.51 ± 1.00 mm) versus MMAT + MTLR (2.93 ± 0.79 mm) approached statistical significance ($P = .054$; 95% CI −0.01 to 1.18). At the "posterior" position, in the loaded state at 0° of flexion, ME was significantly greater following isolated MMAT (2.43 ± 1.10 mm) compared with MMAT + MTLR (1.96 ± 0.99 mm; $P = .010$; 95% CI 0.14-0.80). No significant differences were found at other flexion angles and loading states in the "anterior," "middle," or "posterior" measurement positions (Table 1).

Table 4. Within-Group Significance Testing of 0° Versus 30° Knee Flexion (*P* Values Only; Refer to Table 1 for Actual Extrusion Values)

	Testing Parameters	*P* Value of 0° vs 30°	95% Confidence Interval [Lower Bound, Upper Bound]
MMAT alone	0 N, anterior	.155	[−0.27, 1.62]
	0 N, middle	**<.001**	[1.09, 2.57]
	0 N, posterior	.125	[−1.08, 0.16]
	0 N, "total extrusion"	**.049**	[0.00, 1.05]
	1000 N, anterior	**.018**	[0.24, 2.00]
	1000 N, middle	.012	[0.39, 2.12]
	1000 N, posterior	.237	[−1.81, 0.73]
	1000 N, "total extrusion"	**.119**	[−0.14, 1.12]
MMAT plus MTLR	0 N, anterior	**.003**	[0.32, 1.16]
	0 N, middle	**.020**	[0.26, 2.06]
	0 N, posterior	.078	[−1.60, 0.10]
	0 N, "total extrusion"	.224	[−0.19, 0.79]
	1000 N, anterior	**.001**	[0.50, 1.46]
	1000 N, middle	.119	[−0.36, 2.45]
	1000 N, posterior	.059	[−2.06, 0.04]
	1000 N, "total extrusion"	.395	[−0.36, 0.88]

P values in bold represent statistical significance ($P < .05$).
MMAT, medial meniscus allograft transplantation; MTLR, meniscotibial ligament reconstruction; N, newtons.

When considering within-group comparisons of ME between "anterior," "middle," and "posterior" measurement positions, significant differences were found for all testing combinations, with the exception of 30° of knee flexion with no axial load for the MMAT alone group ($P = .123$). All significant post-hoc pairwise comparisons (e.g., "anterior" vs "middle," "anterior" vs "posterior") are presented in Table 2.

Mean ME was greater in the loaded state compared to the unloaded state for all testing combinations in each group (Table 1). Significant pairwise comparisons are presented in Table 3. When considering differences in ME based on flexion angles, ME was greater at 0° compared to 30° for measurements at the "anterior" and "middle" positions, while ME was greater at 30° for measurements at the "posterior" position (Table 1). Significant pairwise comparisons are presented in Table 4.

Discussion

The main findings of this investigation were that "mean total extrusion" and ME measured from the "posterior" position were significantly greater following isolated MMAT (mean total extrusion: 2.56 ± 1.23 mm; "posterior" extrusion: 2.43 ± 1.10 mm) compared with MMAT + MTLR (mean total extrusion: 2.14 ± 1.07 mm; "posterior" extrusion" 1.96 ± 0.99 mm) when knees were loaded and in extension. Despite a statistically significant difference, the absolute change in ME measured less than 1 mm. Moreover, ME was greater at the "middle" and "posterior" aspects of the joint line compared with the "anterior" aspect in both groups.

The findings of the present study add to a growing body of literature investigating links between surgical techniques to address meniscal pathology and associated biomechanical outcomes. While statistically significant differences in ME were appreciated in certain conditions following the application of MTLR, the clinical implication remains unknown, given the small degree of extrusion when quantifying values. The amount of ME considered relevant remains controversial. The most commonly accepted value to define significant extrusion indicative of meniscal pathology on magnetic resonance imaging is 3 mm.[36] Meanwhile, Muzaffar et al.[37] suggested that any extrusion greater than 2 mm could be considered significant. If threshold values of 2 or 3 mm are considered, there were several conditions in the present experiment in which the addition of MTLR brought the amount of extrusion from a level above the threshold to a value below. However, these differences are small and it is not known whether a reduction of less than one mm in which both values stay above the threshold (e.g., 4.75-4.25 mm) is biomechanically or clinically relevant when compared with a reduction crossing a threshold (e.g., 3.25-2.75 mm). Interestingly, in a cadaveric biomechanical model, Debieux et al.[19] found an ME cut-off of 4 mm for altered force distribution within the medial compartment. Given these findings, perhaps any extrusion below 4 mm may be of negligible import. To address these uncertainties, further biomechanical study and clinical correlation is warranted.

Several authors have evaluated techniques to reduce meniscal extrusion in both native meniscus models and post-MAT models. It is difficult to draw direct comparisons between these various studies due to the heterogeneity in repair/reconstruction techniques, loading protocols, and outcomes assessed. With these caveats, our findings are comparable with those described by Paletta et al.,[31] who demonstrated the biomechanical utility of repair of the medial MTL in reducing ME following transection of the posterior meniscal root in a cadaveric model. Their model was based on a native meniscus and MTL, rather than a transplanted meniscal allograft with a "skirt" of meniscocapsular tissue preserved and used to perform MTLR, as presented in the current study.[31] Further, Paletta et al.[31] used 3 anchor-based repair sutures (3.0 SutureTak anchors with 2-0 FiberWire sutures; Arthrex) rather than the 2 anchors used in the present study, and they performed load cycling and applied a 10 N-m varus thrust at the time of extrusion measurement. Under these conditions, Paletta et al.[31] reported a reduction in ultrasonographically measured ME from 3.4 ± 0.7 mm to 2.1 ± 0.4 mm following MTL repair. The authors did not report the ultrasound measurement location relative to the MCL, so comparisons based on location of extrusion cannot be assessed. Both studies report small but significant differences in extrusion following repair or reconstruction of the meniscotibial ligament, underscoring the importance of this structure as a constraint to ME.

Other peripheral fixation techniques during MAT have been described. Hewison et al.[22] reported using a single point of peripheral fixation in a cadaveric MAT model, reporting no significant reduction in ME. Hewison et al.[22] used a peripheral soft-tissue and transosseous tunnel-root fixation MAT technique, augmented with an additional point of fixation at the mid-body of the meniscus via an additional transosseous tunnel. They did not report the suture material or size. While comparing differences in ME based on peripheral fixation technique is difficult due to the heterogeneity of surgical procedures and testing protocols, a trend toward reduced extrusion with greater than one point of peripheral fixation, as suggested by the results of the present study, is plausible. It is known that strong root attachments allow the meniscus to maintain circular tension and distribute hoop stresses.[38] However, it is also known that MTL disruption alone, with intact roots, leads to meniscal extrusion and impaired force distribution.[19] Perhaps, by repairing or reconstructing the MTL, hoop stresses are dissipated and extrusion reduced. This suggestion is supported by the findings of Merkely et al.,[25] who documented a significant reduction in lateral ME using an open bridge-in-slot MAT technique using 5-6 peripheral-based repair sutures (No. 0 ETHIBOND; Ethicon, Raritan, NJ) passed directly through the tibial cortex (1.2 ± 2.0 mm) when compared with an arthroscopic technique that used capsular-based peripheral repair sutures alone (2.4 ± 1.9 mm; $P = .033$).

In the present study, 2 points of bony fixation were used along the periphery, which is more than the 1 point used by Hewison et al.,[22] but less than the 5 to 6 used by Merkely et al.,[25] and fewer than the 3 used by Paletta et al.[31] in their study of MTL repair of the native meniscus. Interestingly, Debieux et al.,[19] in their biomechanical study of native meniscal extrusion, determined that a meniscus repair construct with 2 points of suture anchor-based peripheral fixation (3.0 SutureTak anchors with 2-0 FiberWire sutures; Arthrex), similar to that in the present study, was capable of reducing medial compartment contact area to a level akin to the intact state when compared to an MTL-deficient, 4-mm extruded state. Further study with standardized conditions is necessary to determine the optimal peripheral fixation technique to ensure a stable transplant.

Despite the complex nature of post-MAT tibiofemoral joint mechanics and heterogeneity within the literature on this topic, a strength of the present study is the comprehensive measurement of extrusion at different locations. While we did not directly measure tibiofemoral load distribution and contact pressures, previous clinical work has demonstrated that the location of ME impacts trends of tibiofemoral cartilage wear in patients with OA.[17] To precisely measure changes due to our reconstruction technique, ME was measured at 3 different areas along the joint line, which allowed for some inference into the locations at which pressures are elevated. ME was lowest at the "anterior" joint line, consistent with the anterior horn of the medial meniscus possessing a smaller cross-sectional area when compared with the posterior horn.[39] This finding is also in-line with the work of Wang et al.,[40] who measured contact forces in tibial plateaus of cadaveric specimens during simulated gait and reported higher forces at the posterior aspect of the medial plateau compared with the anterior aspect. Following our reconstruction technique, extrusion in the loaded state at 0° of flexion was greater at the "middle" position for both isolated MMAT and MMAT + MTLR when compared with measurements performed in the "posterior" position. However, in the loaded state at 30° of flexion, the trend reversed, with ME being greater following both isolated MMAT and MMAT + MTLR at the "posterior" position compared with the "middle" position. Again, this finding is unsurprising as it is known that the medial meniscus moves posteriorly as the knee flexes.[41] Future studies of MTLR should measure ME at multiple points along the joint line, and also correlate positional ME data with tibiofemoral contact force data.

Limitations

This study is not without limitations. While the use of ultrasound for ME measurements has been validated, it remains uncommonly performed in the clinical setting, potentially decreasing the clinical applicability of our findings.[42] Further, there is concern for the user-dependent variability of ultrasonography. A limitation of the chosen loading protocol is that loads were not cycled as is sometimes performed in biomechanical loading studies to simulate in vivo repetitive loading,[31] Another limitation is that extrusion was measured only at flexion angles of 0° and 30°; as a result, differences at deeper flexion angles cannot be gleaned. A final limitation is that biomechanical factors such as tibiofemoral contact pressure and load distribution were not assessed.

Conclusions

Following MMAT, the addition of MTLR significantly reduced overall ME when compared with isolated MMAT during loading at 0° of flexion in a cadaveric model; given the small absolute values of change in extrusion, clinical significance cannot be gleaned from these findings.

References

1. Aagaard H, Verdonk R. Function of the normal meniscus and consequences of meniscal resection. *Scand J Med Sci Sports* 1999;9:134-140.
2. Faunø P, Nielsen AB. Arthroscopic partial meniscectomy: A long-term follow-up. *Arthroscopy* 1992;8:345-349.
3. Hunter D. Degeneration of the meniscus and progression of osteoarthritis. *HSS J* 2012;8:13-14.
4. Lanzer WL, Komenda G. Changes in articular cartilage after meniscectomy. *Clin Orthop Relat Res* 1990;(252): 41-48.
5. Roos H, Lauren M, Adalberth T, Roos EM, Jonsson K, Lohmander LS. Knee osteoarthritis after meniscectomy: Prevalence of radiographic changes after twenty-one years, compared with matched controls. *Arthritis Rheum* 1998;41:687-693.
6. A Cavendish P, Dibartola AC, Everhart JS, Kuzma S, Kim WJ, Flanigan DC. Meniscal allograft transplantation: a review of indications, techniques, and outcomes. *Knee Surg Sports Traumatol Arthrosc* 2020;28:3539-3550.
7. Kim JM, Bin SI, Lee BS, et al. Long-term survival analysis of meniscus allograft transplantation with bone fixation. *Arthroscopy* 2017;33:387-393.
8. Hommen JP, Applegate GR, Del Pizzo W. Meniscus allograft transplantation: Ten-year results of cryopreserved allografts. *Arthroscopy* 2007;23:388-393.

9. Van Der Straeten C, Byttebier P, Eeckhoudt A, Victor J. Meniscal allograft transplantation does not prevent or delay progression of knee osteoarthritis. *PLoS One* 2016;11:e0156183.
10. De Bruycker M, Verdonk PCM, Verdonk RC. Meniscal allograft transplantation: A meta-analysis. *Sicot-J* 2017;3:33.
11. Ahn JH, Kang HW, Yang TY, Lee JY. Risk factors for radiographic progression of osteoarthritis after meniscus allograft transplantation. *Arthroscopy* 2016;32:2539-2546.
12. Lee D-H. Incidence and extent of graft extrusion following meniscus allograft transplantation. *BioMed Res Int* 2018;2018:1-11.
13. Lee D-H, Kim T-H, Lee S-H, Kim C-W, Kim J-M, Bin S-I. Evaluation of meniscus allograft transplantation with serial magnetic resonance imaging during the first postoperative year: Focus on graft extrusion. *Arthroscopy* 2008;24:1115-1121.
14. Samitier G, Alentorn-Geli E, Taylor DC, et al. Meniscal allograft transplantation. Part 1: Systematic review of graft biology, graft shrinkage, graft extrusion, graft sizing, and graft fixation. *Knee Surg Sports Traumatol Arthrosc* 2015;23:310-322.
15. Lee D-H, Kim S-B, Kim T-H, Cha E-J, Bin S-I. Midterm outcomes after meniscal allograft transplantation. *Am J Sports Med* 2010;38:247-254.
16. Ha JK, Shim JC, Kim DW, Lee YS, Ra HJ, Kim JG. Relationship between meniscal extrusion and various clinical findings after meniscus allograft transplantation. *Am J Sports Med* 2010;38:2448-2455.
17. Bloecker K, Wirth W, Guermazi A, et al. Relationship between medial meniscal extrusion and cartilage loss in specific femorotibial subregions: Data from the osteoarthritis initiative. *Arthritis Care Res* 2015;67:1545-1552.
18. Wang D-Y, Zhang B, Li Y-Z, Meng X-Y, Jiang D, Yu J-K. The long-term chondroprotective effect of meniscal allograft transplant: A 10- to 14-year follow-up study. *Am J Sports Med* 2022;50:128-137.
19. Debieux P, Jimenez AE, Novaretti JV, et al. Medial meniscal extrusion greater than 4 mm reduces medial tibiofemoral compartment contact area: A biomechanical analysis of tibiofemoral contact area and pressures with varying amounts of meniscal extrusion. *Knee Surg Sports Traumatol Arthrosc* 2021;29:3124-3132.
20. Lubowitz JH, Verdonk PC, Reid JB 3rd, Verdonk R. Meniscus allograft transplantation: A current concepts review. *Knee Surg Sports Traumatol Arthrosc* 2007;15:476-492.
21. Bin S-I, Kim H-J, Lee D-H. Graft extrusion after medial and lateral MAT differs according to surgical technique: A meta-analysis. *Arch Orthop Trauma Surg* 2018;138:843-850.
22. Hewison C, Kolaczek S, Caterine S, et al. Peripheral fixation of meniscal allograft does not reduce coronal extrusion under physiological load. *Knee Surg Sports Traumatol Arthrosc* 2019;27:1924-1930.
23. Jung Y-H, Choi N-H, Victoroff BN. Arthroscopic stabilization of the lateral capsule of the knee in meniscal transplantation. *Knee Surg Sports Traumatol Arthrosc* 2011;19:189-191.
24. Masferrer-Pino A, Monllau JC, Abat F, Gelber PE. Capsular fixation limits graft extrusion in lateral meniscal allograft transplantation. *Int Orthop* 2019;43:2549-2556.
25. Merkely G, Ogura T, Ackermann J, Mestriner AB, Minas T, Gomoll AH. Open meniscal allograft transplantation with transosseous suture fixation of the meniscal body significantly decreases meniscal extrusion rate compared with arthroscopic technique. *Arthroscopy* 2019;35:1658-1666.
26. Monllau JC, Ibañez M, Masferrer-Pino A, Gelber PE, Erquicia JI, Pelfort X. Lateral capsular fixation: An implant-free technique to prevent meniscal allograft extrusion. *Arthrosc Tech* 2017;6:e269-e274.
27. Sali E, Hardy A, Grimaud O, Meyer A. An original all-arthroscopic technique for bony fixation of lateral meniscus allograft via four tibial tunnels: A cadaver study. *Orthop Traumatol Surg Res* 2018;104:1205-1208.
28. Stone KR, Walgenbach AW. Meniscal allografting: the three-tunnel technique. *Arthroscopy* 2003;19:426-430.
29. Masferrer-Pino A, Monllau JC, Ibáñez M, Erquicia JI, Pelfort X, Gelber PE. Capsulodesis versus bone trough technique in lateral meniscal allograft transplantation: Graft extrusion and functional results. *Arthroscopy* 2018;34:1879-1888.
30. Krych AJ, Bernard CD, Leland DP, et al. Isolated meniscus extrusion associated with meniscotibial ligament abnormality. *Knee Surg Sports Traumatol Arthrosc* 2020;28:3599-3605.
31. Paletta GA, Crane DM, Konicek J, et al. Surgical treatment of meniscal extrusion: A biomechanical study on the role of the medial meniscotibial ligaments with early clinical validation. *Orthop J Sports Med* 2020;8:232596712093667.
32. Pollard ME, Kang Q, Berg EE. Radiographic sizing for meniscal transplantation. *Arthroscopy* 1995;11:684-687.
33. Frank RM, Cole BJ. Meniscus transplantation. *Curr Rev Musculoskelet Med* 2015;8:443-450.
34. Daney BT, Aman ZS, Krob JJ, et al. Utilization of transtibial centralization suture best minimizes extrusion and restores tibiofemoral contact mechanics for anatomic medial meniscal root repairs in a cadaveric model. *Am J Sports Med* 2019;47:1591-1600.
35. Özdemir M, Turan A. Correlation between medial meniscal extrusion determined by dynamic ultrasound and magnetic resonance imaging findings of medial-type knee osteoarthritis in patients with knee pain. *J Ultrasound Med* 2019;38:2709-2719.
36. Costa CR, Morrison WB, Carrino JA. Medial meniscus extrusion on knee MRI: Is extent associated with severity of degeneration or type of tear? *AJR Am J Roentgenol* 2004;183:17-23.
37. Muzaffar N, Kirmani O, Ahsan M, Ahmad S. Meniscal extrusion in the knee: Should only 3 mm extrusion be considered significant? An assessment by MRI and arthroscopy. *Malay Orthop J* 2015;9:17-20.
38. Wang J-Y, Qi Y-S, Bao H-R-C, et al. The effects of different repair methods for a posterior root tear of the lateral meniscus on the biomechanics of the knee: A finite element analysis. *J Orthop Surg Res* 2021;16:296.
39. Bryceland JK, Powell AJ, Nunn T. Knee Menisci. *CARTILAGE* 2017;8:99-104.

40. Wang H, Chen T, Torzilli P, Warren R, Maher S. Dynamic contact stress patterns on the tibial plateaus during simulated gait: A novel application of normalized cross correlation. *J Biomech* 2014;47:568-574.

41. Thompson WO, Thaete FL, Fu FH, Dye SF. Tibial meniscal dynamics using three-dimensional reconstruction of magnetic resonance images. *Am J Sports Med* 1991;19:210-216.

42. Verdonk P, Depaepe Y, Desmyter S, et al. Normal and transplanted lateral knee menisci: Evaluation of extrusion using magnetic resonance imaging and ultrasound. *Knee Surg Sports Traumatol Arthrosc* 2004;12:411-419.