

Pediatric Meniscotibial Ligament Complex Anatomy and Biomechanics

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Background: Meniscal repair is increasingly performed in pediatric patients, with capsular-based techniques remaining the gold standard despite limitations such as high failure rates and risk of meniscal extrusion. Recent studies highlight the potential role of accessory knee ligaments in improving meniscal stability and repair outcomes. The meniscotibial ligament complex (MTLC) has emerged as a potential area of interest to produce more normal anatomic and biomechanical meniscal function in meniscal repair.

Purpose: To evaluate the native anatomy and biomechanical strength of the MTLC of the medial and lateral meniscus of pediatric knees.

Study Design: Descriptive laboratory study.

Methods: Fourteen fresh-frozen pediatric human knees (mean age, 7.5 years; range, 5-10 years; 6 male, 8 female) were used in this study. The depth of the recess between the MTLC and the meniscocapsular complex was measured. Subsequently, the medial and lateral menisci were divided into approximate thirds, creating anterior, central, and posterior testing zones for each meniscus. Each meniscus/MTLC complex underwent monotonic load-to-failure testing on an Instron 5944 test frame with a 2-kN load cell with load applied superiorly. Biomechanical properties were analyzed using linear mixed models with donor as a random factor and aspect (medial/lateral) and position (anterior/central/posterior) as fixed factors.

Results: The posterior recess depth was significantly larger (mean, 5.4 mm; 95% CI, 4.6-6.3 mm) than anterior (mean, 3.4 mm; 95% CI, 2.6-4.2 mm) ($P = .049$). Maximal load to failure in the posterior MTLC (mean, 93.5 N; 95% CI, 80.0-107.0 N) was significantly higher than anterior (mean, 69.2 N; 95% CI, 56.7-81.7 N) ($P = .01$).

Conclusion: This study defines a clear space in which the MTLC is distinct from the joint capsule, which is deepest in the posterior third of the medial and lateral meniscus. Our results demonstrate that the posterior region of the MTLC can withstand higher loads than the anterior region in pediatric knees.

Clinical Relevance: These findings offer foundational insights into the native anatomy and biomechanics of the MTLC, guiding future studies involving the MTLC in meniscal repair. This knowledge may be particularly relevant to ramp lesions, other posterior meniscal tear patterns, and meniscal transplants.

Keywords: meniscus; meniscal tear; meniscal repair; coronary ligament; meniscotibial ligament complex; meniscal instability

Meniscal injuries are among the most common orthopaedic injuries in the United States, with a progressive rise in rates of meniscal injury and surgical repair in pediatric patients.^{1,2,16} Pediatric patients experience meniscal conditions such as ramp lesions, posterolateral tears, and congenital discoid meniscus, the latter of which may require meniscal allograft transplantation in severe cases.^{4,19,31}

Meniscal preservation surgery is increasingly prioritized in younger patients to slow the progression of early-onset osteoarthritis.^{21,30,32} Meniscal repairs frequently achieve stability via meniscocapsular complex (MCC)-based repair techniques in pediatric and adult patients by tying sutures directly on the capsule (inside-out, outside-in repairs) or deploying suture anchors through the capsule (some all-inside repairs).^{21,22,36} Repairs involving the joint capsule have been demonstrated to provide biomechanically strong and clinically efficacious fixation for various meniscal tear patterns.^{13,15,23} However, shortcomings of capsular-based

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repairs include risk of damaging surrounding soft tissue and neurovascular structures, hyperstability that can lead to retearing, restricted range of motion postoperatively, and meniscal extrusion.^{15,22,38} Furthermore, the reoperation rate for isolated meniscal repairs remains high at about 20% for all ages, with reported failure rates similar for pediatric and adult populations.^{28,33} While capsular-based techniques are the current gold standard for meniscal repair,^{22,23,26} exploration of ways to improve meniscal repair continues to be an active area of study.

One such area of interest has been in better understanding the role of other accessory ligaments in the knee that may increase stability and affect clinical outcomes. Recent biomechanical studies in adult tissues have examined the role of the meniscotibial ligament, a small fibrous band from the meniscus to the tibia, and found that reconstruction of the medial meniscotibial ligament reduces meniscal extrusion in capsular-based meniscal repair and transplantation.^{5,6,14,27} Other biomechanical studies on fully meniscus-based repairs, which avoid suturing the meniscus to the capsule, have been conducted that show equal strength to capsular-based techniques.^{11,15,25} However, a limitation of these comparisons is that they do not include the actual joint capsule, just the isolated menisci. Some have proposed that the theoretical advantages of meniscus-based repair include improved meniscal mobility and reduced risk of meniscal extrusion because the meniscus is not tethered to the joint capsule.^{15,38}

This led to our interest in studying the anatomy and strength of the meniscotibial ligament complex (MTLC), a sheet of organized fibrous connective tissue that connects the medial and lateral menisci to the tibia, which includes the meniscotibial ligament as discussed above.²⁴ The MTLC runs continuously from the anterior to the posterior menisci, only interrupted at the level of the popliteal hiatus along with the joint capsule on the lateral side of the knee.^{10,16} A previous anatomic study has identified a distinct plane between the posterior knee capsule and the MTLC in pediatric knees.¹⁰ We sought to better characterize this structure, given the growing interest in meniscus-based repairs and the lack of previous biomechanical studies on the MTLC in both pediatric and adult tissues.

Our objective was to evaluate the anatomy and regional biomechanical strength of the MTLC of the medial and lateral menisci of pediatric knees. We hypothesized that (1) posterior anatomy of the medial and lateral knee would demonstrate a consistent recess or space between the MTLC complex and the surrounding MCC and (2) the MTLC would demonstrate distinct biomechanical

characteristics between the posterior, central, and anterior thirds of the medial and lateral menisci.

METHODS

This was a descriptive cadaveric study performed in the biomechanical testing lab of our facility. Fourteen fresh-frozen pediatric cadaveric knee specimens from 10 donors (mean age, 7.5 years; range, 5-10 years; 6 male, 8 female) were used in this study. The deidentified juvenile knee specimens were donated to the university for research purposes by a human tissue nonprofit organization. The specimens were dissected by a group of 6 board-certified pediatric and sports medicine orthopaedic surgeons (M.T., H.B.E., T.J.G., Y.-M.Y., M.R.S., and K.G.S.) assisted by medical students, residents, and fellows using the following dissection protocol. A lateral arthrotomy was performed adjacent to the patella. Subsequently, the iliotibial band, the patellar tendon, the patella, and the quadriceps muscle were removed. The joint capsule was circumferentially released off the femur and released above the popliteus laterally. The capsule was preserved 2 to 4 cm above the joint line for measurement of the recess space between the MTLC and the MCC. All specimens were stored at -20°C after dissection and thawed at room temperature for 24 hours before measurement and biomechanical testing.

We measured the distance between the inferiormost aspect of the joint capsule attached to the MTLC and the superiormost aspect of the meniscus (which was the most superior point of the MTLC attachment to the meniscus). Measurements were taken viewing superior to inferior in an axial direction using a depth gauge and digital caliper. We defined this distance as the “depth of the recess” between the MTLC and the MCC (Figure 1, A and B). The MCC was manually suspended in an upright position to recreate the normal anatomic position without introducing significant tension when measuring the recess depth by gently lifting the MCC layer proximally along the axis of the tibia with forceps.

Subsequently, the medial and lateral menisci were divided into approximate thirds with radial cuts extending through the meniscotibial ligaments, creating anterior, central, and posterior testing zones for each meniscus (Figure 1C). The posterior and anterior roots of each meniscus were released from the tibial attachment to isolate the biomechanical properties of the MTLC without the confounding influence of root attachments, which are known to significantly contribute to the strength and load

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Ethical approval was deemed not necessary for the present study.

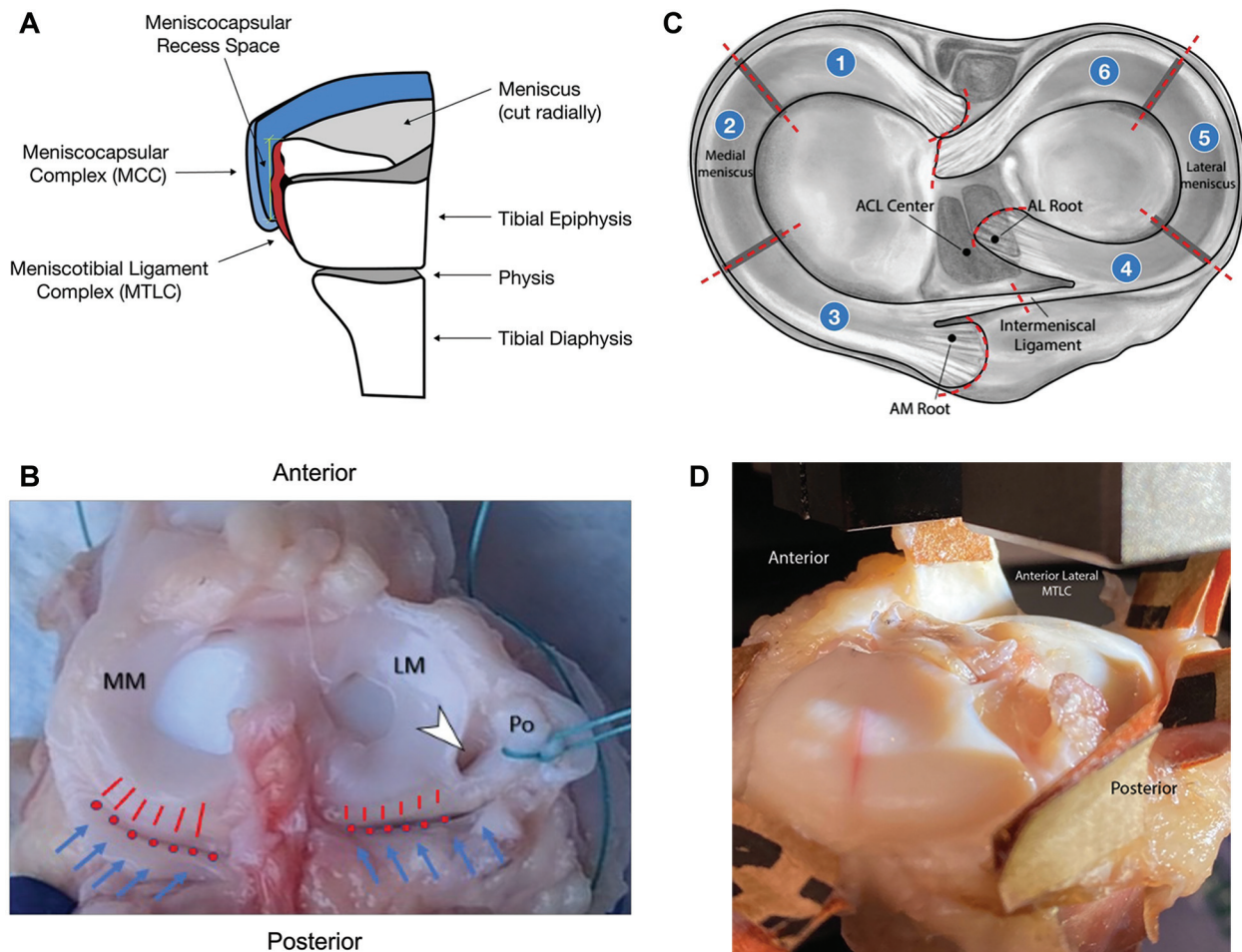


Figure 1. Defining the meniscotibial ligament complex (MTLC) and isolating its anterior, central, and posterior aspects for biomechanical testing. (A) Schematic of a coronal cross section of half of a knee. The MTLC is depicted in red. The meniscocapsular recess space is indicated between the MTLC and the meniscocapsular complex (MCC, or joint capsule). The meniscocapsular recess space measurements were taken as indicated by the yellow line from the inferiormost point of the recess to the top of the meniscus, measured in the axial direction. (B) Gross examination of pediatric knee specimen indicating the distinct space that separates the MTLC and the MCC in the posterior aspect of the medial and lateral menisci. The distinct space also exists in the anterior and central regions but is only indicated in the posterior aspect in this image. The large white arrowhead indicates the popliteal hiatus. The small red lines indicate the MTLC, the small blue arrows indicate the MCC, and the small red circles show the meniscocapsular recess. MM, medial meniscus; LM, lateral meniscus; Po, popliteal tendon. (C) Axial schematic of radial meniscal transections, adapted from Dingel et al.¹⁰ Areas with red dashed line indicate where a scalpel was used to release the meniscus roots or transect the meniscus/MTLC complex into thirds. Numbered regions correspond to the segments of the meniscus/MTLC complex that subsequently underwent biomechanical testing: 1. Medial posterior; 2. Medial central; 3. Medial anterior; 4. Lateral anterior; 5. Lateral central; 6. Lateral posterior. ACL, anterior cruciate ligament; AL, anterolateral; AM, anteromedial. (D) Clamp on the anterior one-third of the lateral meniscus pulling vertically on the MTLC to failure. The tibia was potted in fiberglass resin and was vertically mounted on the Instron 5944 test frame.

distribution of the meniscus.¹² The meniscal segments were flipped outward radially 180° to take measurements of the meniscus and MTLC on the side that interfaced with the tibia (Supplemental Figure S1A). Measurements were taken with digital calipers of each MTLC segment length, width, and thickness (Supplemental Figure S1B). The length of the MTLC section was calculated by measuring the distance from the furthest edge of the meniscus to the insertion point of the MTLC on the tibia, measuring the length of the meniscus (Supplemental Figure S1C),

and subtracting the values. The width of each MTLC section was measured with flexible suture to account for the curvature of the meniscus at the juncture of the meniscus and the MTLC on the “inside,” which lies on top of the tibia in native anatomy. The flexible suture length was then measured with digital calipers, corresponding to the meniscal width. The thickness of the MTLC was measured at the thickest point for each specimen, which was at the interface with the meniscus (Supplemental Figure S1D), and at the thinnest point, which was at the insertion point

on the tibia (Supplemental Figure S1E). Because the segments were dissected into approximate thirds, the variation in meniscal width was reported (Supplemental Figure S2, A and B).

Each tibial specimen was potted in Bondo epoxy putty (3M) in square molds. To prepare sections for mechanical testing, 2 rectangles of 100-grit sandpaper were glued to the anterior and posterior sides of each meniscal segment using cyanoacrylate (Gorilla Super Glue) with hemostats to compress the sandpaper meniscal sandwich. The sandpaper grit faced toward the meniscus, and the sandpaper rectangles were large enough to encapsulate the entire meniscus but did not overlap with the MTLC. The sandpaper was used to reduce slippage of the meniscus in the Instron clamp without interfering with the native MTLC. Each specimen was visually inspected by ≥ 2 of the following study authors (W.H.V.D., T.M.J., A.C.-M., D.R.W.B.) to confirm the absence of MTLC contact with sandpaper and to ensure complete coverage of the entire meniscal segment.

Once dried, each tibial specimen was mounted on an Instron 5944 electromechanical load frame with a 2-kN load cell. The tibia was rigidly mounted to prevent any movement during testing, and the meniscal section was clamped in the mobile grip. Precautions were taken to ensure even gripping of the sample so as not to prestress one side of the specimen. Loading was applied in the superior direction, as it provided the most uniform load on the MTLC. A preload was applied before testing by setting the extension to 0 mm at 1 N. Each meniscus/MTLC complex underwent 10 cycles of preconditioning from 3 to 5 N at 10 mm/min followed by load to failure testing at 10 mm/min (Figure 1D). The load and displacement were recorded as each specimen underwent load-to-failure testing (Supplemental Figure S3A). Load-displacement curves were plotted for each specimen. For each load-displacement curve, the maximal load and displacement at maximal load were extracted by identifying the highest point on the load-displacement curve (Supplemental Figure S3B).

For each segment tested, the stiffness was calculated manually by selecting a linear region close to maximal load and using the formula $stiffness = \frac{\text{Change in load}}{\text{Change in displacement}}$ (Supplemental Figure S3B). The work to maximum was calculated using the trapezoidal rule: $Work = \sum_{i=1}^{n-1} \frac{1}{2} (y_i + y_{i+1}) \cdot (x_{i+1} - x_i)$, where n is the number of data points, x_i and x_{i+1} are consecutive displacement values, and y_i and y_{i+1} are corresponding force values. The failure stress at the interface of the meniscus and the MTLC was estimated by dividing the maximal load by the maximal cross-sectional area: $failure\ stress = \frac{Max\ load}{MTLC\ length * MTLC\ max\ thickness}$, with the observation that the maximal thickness was measured where the MTLC interfaced with the meniscus (the minimal cross-sectional area was measured where the MTLC attached to the tibia). Strain at maximal load was calculated as $strain = \frac{Displacement\ at\ max\ load}{MTLC\ length\ at\ rest}$. When the specimen was mounted with a superior load applied, the MTLC length corresponded to the vertical measurement, and the width corresponded to the horizontal measurement in this orientation.

Throughout biomechanical testing, specimens were kept moist with normal saline. All testing occurred at room temperature. For some of the segments, we observed slippage of the clamped meniscal specimens from the glued sandpaper. For these specimens, any displaced sandpaper was removed and new sandpaper was applied. Consequently, multiple attempts were made for these specimens until each MTLC segment reached failure, and any attempt with slippage was discarded. The distribution of attempts was as follows: 58 samples had 1 attempt; 15 samples had 2 attempts; 6 samples had 3 attempts; 2 samples had 4 attempts.

Statistical analyses were performed using RStudio Version 2023.03.1 + 446 (Posit PBC). Each outcome was analyzed using a linear mixed model with donor as a random factor and aspect (medial/lateral) and position (anterior/central/posterior) as fixed factors. To assess the potential effect of age and size on biomechanical outcomes, age was included as a fixed effect in the model. Additionally, meniscal length, a surrogate for size that has been previously described to increase with age, was analyzed as a continuous variable in place of age.³⁷ One model, the displacement at maximal load, with nonnormal residuals ($|skewness| \geq 2$) was reanalyzed with log-transformed outcomes. All other models had residuals that were sufficiently normal and did not undergo data transformation. Significance was at $P < .05$ and Bonferroni modification was used for pairwise comparisons. Results are reported as (mean; 95% CI).

RESULTS

The depth of recess was significantly larger in the posterior region (mean, 5.4 mm; 95% CI, 4.6-6.3 mm) than in the anterior region (mean, 3.4 mm; 95% CI, 2.6-4.2 mm) ($P = .049$), with no significant difference between medial and lateral menisci (Figure 2A).

For the structural biomechanical properties of the MTLC, the maximal load, displacement at maximal load, stiffness as extracted from load-displacement curves, and work to maximal load were analyzed. In this text, the maximal load refers to the load at the time of failure. The maximal load in the posterior MTLC region (mean, 93.5 N; 95% CI, 80.0-107.0 N) was significantly higher than in the anterior region (mean, 69.2 N; 95% CI, 56.7-81.7 N) ($P = .01$), with no other differences between aspect or position (Figure 3A). The displacement at maximal load was significantly lower in medial (mean, 9.9 mm; 95% CI, 8.7-11.2 mm) than lateral MTLC specimens (mean, 15.2 mm; 95% CI, 12.3-18.0 mm) ($P < .001$), as well as significantly lower in the anterior (mean, 11.0 mm; 95% CI, 8.1-14.0 mm) than the posterior MTLC (mean, 13.5 mm; 95% CI, 11.5-15.4 mm) ($P = .04$) (Figure 3B). The stiffness of the MTLC showed no statistically significant differences by position or aspect (Figure 3C). The work to maximal load was significantly higher in the lateral (mean, 698.5 N-mm; 95% CI, 555.0-842.1 N-mm) than the medial MTLC segments (mean, 482.6 N-mm; 95% CI, 352.5-612.8 N-mm) ($P = .03$), with no significant differences by position (Figure 3D).

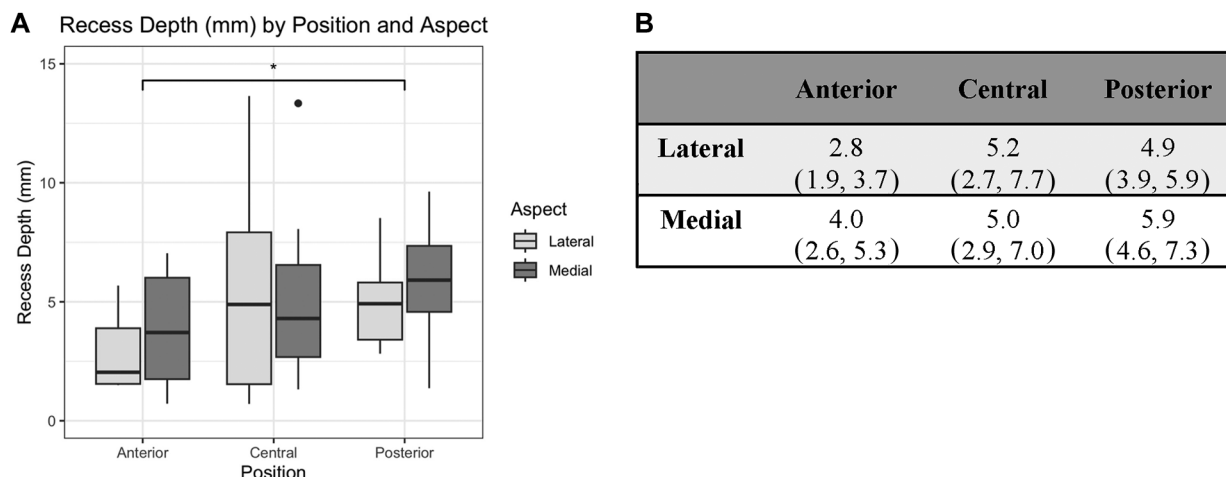


Figure 2. A distinct separation exists between the meniscotibial ligament complex (MTLC) and the meniscal capsular complex. (A) Meniscocapsular recess depth of the anterior, central, and posterior regions of the lateral and medial menisci. Measurements were taken using a depth gauge and digital calipers at the deepest point of the recess between the meniscal capsular complex and the MTLC before the meniscus was transected into thirds to maintain the anatomic position of the capsule before biomechanical testing. Asterisk indicates significance at $P < .05$. Solid black dots indicate outliers beyond 1.5 times the interquartile range. (B) Summary table of mean recess depth for each unique aspect and position. Values are reported as mean (95% CI).

For the material biomechanical properties of the MTLC, the failure stress and strain at peak load were calculated. We observed that most failure occurred at the junction between the MTLC and the meniscus, where the cross-sectional area was largest due to the maximal thickness of the MTLC in this region. The failure stress was found to be higher in central (mean, 6.9 MPa; 95% CI, 5.1-8.8 MPa) than in anterior MTLC segments (mean, 4.1 MPa; 95% CI, 2.8-5.4 MPa) ($P = .004$), with no significant difference by aspect (Figure 4A). Strain at peak load was found to be significantly higher in medial (mean, 2.7 mm/mm; 95% CI, 2.1-3.3 mm/mm) than in lateral (1.6 mm/mm; 95% CI, 1.2-1.9 mm/mm) ($P < .001$) MTLC segments, with no other difference between regions (Figure 4B). Results of biomechanical testing by aspect and position are summarized in Supplemental Table S1.

Age was not a significant predictor of load to failure ($P = .23$; 95% CI, -1.8-8.8). Using meniscal length as a continuous variable in place of age also showed no significant effect on load to failure ($P = .59$). Given the limited sample size ($N = 14$), the study was underpowered to detect significant effects of age or size on biomechanical outcomes.

DISCUSSION

In this study, we measured a distinct separation between the MTLC and the MCC that was deepest in the posterior third of the medial and lateral menisci compared with the anterior third. Our study was the first to measure the biomechanical properties of the MTLC in the anterior, central, and posterior regions of pediatric knee specimens, including the load to failure, displacement at failure, stiffness, work to failure, failure stress at the MTLC-meniscus interface, and

strain at failure. Our results indicate that the posterior region of both the medial and the lateral menisci could withstand higher loads than the anterior region.

A previous study identified a clear posterior recess between the posterior MTLC and the posterior capsule of the knee joint using pediatric knees ages 3 months to 2 years and 10 to 11 years.¹⁰ We expanded on these findings by defining the separation between the MTLC and the joint capsule in the central and anterior regions of the MTLC as well. Furthermore, our specimens were in pediatric knees ages 5 to 10 years, an age range that was not covered in the previous study. Thus, this study adds to the literature supporting the MTLC as a consistently present structure distinct from the joint capsule in pediatric knees.

Several studies have underscored that preserving normal anatomy is important in meniscal repair, especially in challenging meniscal tear patterns and in younger patients.^{17,20,35} A study by LaPrade et al²⁰ found that non-anatomic posterior medial meniscus root repairs do not restore tibiofemoral contact mechanics to the same extent as anatomic repairs, emphasizing the importance of releasing extruded menisci from adhesions to the capsule to achieve optimal repair outcomes. Furthermore, studies have described how tears in meniscocapsular and meniscotibial ligaments can contribute to further knee instability with anterior tibial translation and knee rotation,^{3,7,9,29} suggesting the meniscotibial ligament plays an important role in knee and meniscal stability as an entity distinct from the joint capsule. On the basis of our consistent observation of a recess between the MTLC and the joint capsule, we speculate that preserving this anatomic feature during meniscal repair could influence clinical outcomes. A recent study in pediatric knees showed that suture anchor fixation of the posterolateral and posteromedial MTLC directly to

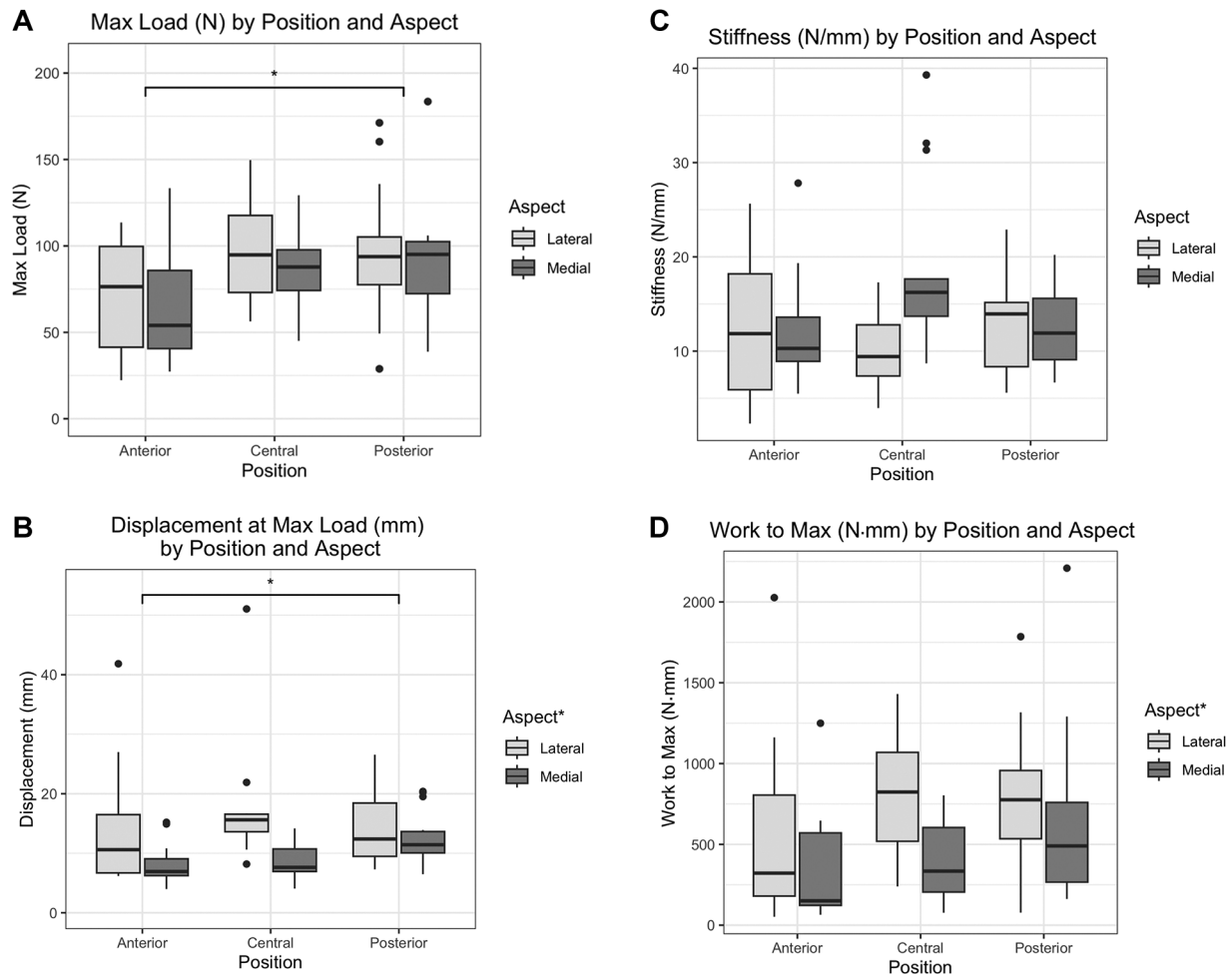


Figure 3. Structural biomechanical properties of the meniscotibial ligament complex (MTLC) by aspect and position. (A) Load to failure (N) of the anterior, central, and posterior regions of the lateral and medial MTLC. The posterior position was significantly higher than the anterior position ($P = .01$), with no difference between aspects. (B) Displacement (mm) at maximal load. After log transformation to correct for nonnormal residuals, the medial aspect was significantly lower than the lateral aspect ($P < .001$), and the anterior position was significantly lower than the posterior position ($P = .04$). (C) Stiffness of the MTLC by aspect and position as calculated from maximal slope of load-displacement curve showed no significant difference among aspect or position. (D) Work to maximal load (N·mm, Newton-millimeters) of the anterior, central, and posterior segments of the lateral and medial MTLC, as calculated using the trapezoidal rule. The work to maximal load in the lateral aspect was significantly greater than the medial aspect ($P = .03$). Asterisk indicates significance at $P < .05$. Solid black dots indicate outliers beyond 1.5 times the interquartile range.

the tibia produced biomechanically strong repairs and preserved the recess, restoring normal knee anatomy.¹⁸ However, it is possible that precise capsular-based repairs that avoid closing the meniscocapsular recess could achieve similar anatomic outcomes. Further studies on preservation of the recess between the MTLC and joint capsule for different meniscal tear patterns are necessary to inform its relevance to surgical practice.

The displacement at maximal load was significantly higher in the lateral than medial MTLC, consistent with the increased flexibility of the lateral meniscus reported.⁸ Similarly, the work to maximal load was significantly higher in the lateral than medial MTLC, indicating that the lateral MTLC has a larger capacity to absorb energy

before failure. While the stiffness of the MTLC did not show any statistically significant differences by position in our study, the strain at failure was higher in the medial than lateral MTLC. This indicates that while the medial MTLC may not stretch as much in absolute terms, it is able to sustain more relative deformation before failure. Interestingly, we observed that most failure occurred at the junction of the meniscus and the MTLC rather than at the junction of the tibia and the MTLC, with the highest stress withstood by the central position. This study examined the biomechanical strength of the native MTLC in pediatric knees, which are free from the degenerative changes associated with aging that are present in studies using adult cadaveric knees.³⁴ It is important to consider

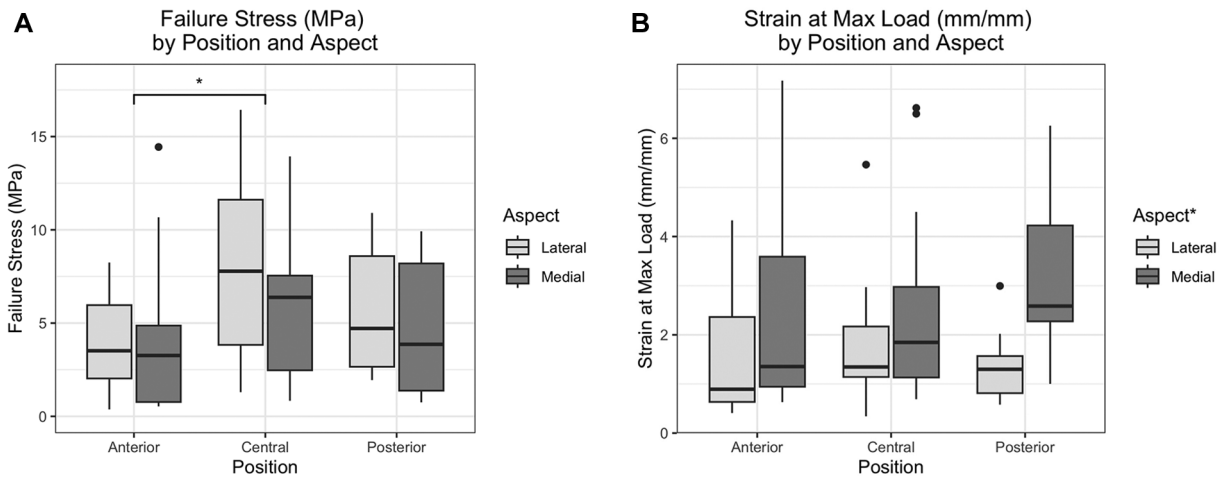


Figure 4. Material biomechanical properties of the meniscotibial ligament complex (MTLC) by aspect and position. (A) Failure stress (MPa) by aspect and position, as calculated by dividing the maximal by the maximal cross-sectional area. The central position was significantly greater than the anterior position ($P = .004$). (B) Strain of the MTLC at maximal load (mm/mm), as calculated by dividing the displacement at maximal load by the MTLC length at rest. The medial aspect was significantly higher as compared with the lateral aspect ($P < .001$). Asterisk indicates significance at $P < .05$. Solid black dots indicate outliers beyond 1.5 times the interquartile range.

that the distinct structures noted in this study of pediatric cadaveric specimens could exist differently or not at all in adult tissues, which are subject to years of degeneration, fibrous tissue accumulation, and other age-related effects.

Limitations

This study is not without its limitations. First, the tissue was from pediatric donors ages 5 to 10, a large enough range over which there could be significant differences in the strength and biomechanical properties of the MTLC by age/size. Due to the exceptionally rare nature of these pediatric specimens, we were unable to get specimens that were all the same age or sex. Age and meniscal length were not found to be significant variables in this study. However, due to the small sample size, their lack of significant effect does not allow us to draw definitive conclusions about age or size dependence on biomechanical outcomes. Second, the menisci were transected into thirds and tested as 3 distinct zones, even though in situ the MTLC is 1 continuous structure. This decision was made given the limitations in mounting and applying a uniform force to a curved structure. Third, multiple attempts were required for some specimens due to slippage of the clamped menisci from the glued sandpaper. We found that clamping the Instron as close to the MTLC-meniscus junction as possible helped reduce slippage, but because the meniscus increases in thickness at this junction, it was difficult to securely clamp the Instron on this wedge-shaped tissue. Fourth, the meniscal width was measured before applying the tare load of 1 N, which may have led to an overestimation of the strain measurement, though we would expect this to be consistent across aspects and positions. Finally, the force on the MTLC in this biomechanical testing was

not representative of the forces on the MTLC in the native state, as we clamped the meniscus and pulled vertically upward. However, this is a common limitation of mechanical testing of cadaveric specimens.²⁷ The superior force could have contributed to the most common location of tissue failure at the interface of the MTLC and the meniscus, although we cannot draw this conclusion without repeating the study using an extrusion force.

CONCLUSION

Overall, this study defines a clear recess space between the MTLC and the joint capsule deepest in the posterior knee and establishes that the posterior MTLC can resist higher loads than the anterior MTLC, for both medial and lateral menisci. These findings provide the foundation for future studies that examine the role of the MTLC in meniscal repair or transplantation, especially in the posterior region of the knee where the MTLC can withstand the highest loads to failure. Given the new findings characterizing the biomechanical strength of the MTLC in all regions, repair of the MTLC to recreate more normal anatomy could be an anatomic approach to improve meniscal repair and stability. These findings support continued development and evaluation of MTLC repair techniques that seek to reproduce the biomechanical and anatomic function of the MTLC, the MCC, and the meniscus.

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REFERENCES

1. Abrams GD, Frank RM, Gupta AK, Harris JD, McCormick FM, Cole BJ. Trends in meniscus repair and meniscectomy in the United States, 2005-2011. *Am J Sports Med.* 2013;41(10):2333-2339.
2. Adams BG, Houston MN, Cameron KL. The epidemiology of meniscus injury. *Sports Med Arthrosc Rev.* 2021;29(3):e24.
3. Ahn JH, Bae TS, Kang KS, Kang SY, Lee SH. Longitudinal tear of the medial meniscus posterior horn in the anterior cruciate ligament-

- deficient knee significantly influences anterior stability. *Am J Sports Med.* 2011;39(10):2187-2193.
4. Bram JT, Mehta NN, Wright ML, Nguyen JC, Leska T, Ganley TJ. Pediatric ramp lesions. *J Pediatr Orthop Soc N Am.* 2020;2(1):48.
5. Cavaignac E, Sylvie R, Teulière M, et al. What is the relationship between the distal semimembranosus tendon and the medial meniscus? A gross and microscopic analysis from the SANTI Study Group. *Am J Sports Med.* 2021;49(2):459-466.
6. Condrón NB, Knapik DM, Gilat R, et al. Concomitant meniscotibial ligament reconstruction decreases meniscal extrusion following medial meniscus allograft transplantation: a cadaveric analysis. *Arthroscopy.* 2022;38(11):3080-3089.
7. Cristiani R, Rönnblad E, Engström B, Forsblad M, Stålmán A. Medial meniscus resection increases and medial meniscus repair preserves anterior knee laxity: a cohort study of 4497 patients with primary anterior cruciate ligament reconstruction. *Am J Sports Med.* 2018;46(2):357-362.
8. Danso EK, Mäkelä JTA, Tanska P, et al. Characterization of site-specific biomechanical properties of human meniscus—importance of collagen and fluid on mechanical nonlinearities. *J Biomech.* 2015;48(8):1499-1507.
9. DePhillipo NN, Moatshe G, Brady A, et al. Effect of meniscocapsular and meniscotibial lesions in ACL-deficient and ACL-reconstructed knees: a biomechanical study. *Am J Sports Med.* 2018;46(10):2422-2431.
10. Dingel AB, Tompkins M, Yen YM, et al. A recess is observed between the posterior knee capsule and the meniscotibial ligament complex in pediatric specimens. *Arthrosc Sports Med Rehabil.* 2024;6(3):100852.
11. Doig T, Fagan P, Frush T, Lovse L, Chen C, Lemos S. The all-inside all-suture technique demonstrated better biomechanical behaviors in meniscus radial tear repair. *Knee Surg Sports Traumatol Arthrosc.* 2020;28(11):3606-3612.
12. Ellman MB, LaPrade CM, Smith SD, et al. Structural properties of the meniscal roots. *Am J Sports Med.* 2014;42(8):1881-1887.
13. Fillingham YA, Riboh JC, Erickson BJ, Bach BR, Yanke AB. Inside-out versus all-inside repair of isolated meniscal tears: an updated systematic review. *Am J Sports Med.* 2017;45(1):234-242.
14. Gilat R, Mitchnik IY, Mimouni T, Agar G, Lindner D, Beer Y. The meniscotibial ligament role in meniscal extrusion: a systematic review and meta-analysis. *Arch Orthop Trauma Surg.* 2023;143(9):5777-5786.
15. Golz AG, Mandelbaum B, Pace JL. All-inside meniscus repair. *Curr Rev Musculoskelet Med.* 2022;15(4):252-258.
16. Grassi A, Pizza N, Lucidi GA, Macchiarola L, Mosca M, Zaffagnini S. Anatomy, magnetic resonance and arthroscopy of the popliteal hiatus of the knee: normal aspect and pathological conditions. *EFORT Open Rev.* 2021;6(1):61-74.
17. Hevesi M, Krych AJ, Kurzweil PR. Meniscus tear management: indications, technique, and outcomes. *Arthroscopy.* 2019;35(9):2542-2544.
18. Hollyer I, Johnstone T, Alayleh A, et al. Suture anchor fixation of the pediatric posteromedial and posterolateral menisco-tibial ligament complex matches or exceeds native tissue strength: a cadaveric study. *J ISAKOS.* 2025;11:100385.
19. Jackson T, Fabricant PD, Beck N, Storey E, Patel NM, Ganley TJ. Epidemiology, injury patterns, and treatment of meniscal tears in pediatric patients: a 16-year experience of a single center. *Orthop J Sports Med.* 2019;7(12):2325967119890325.
20. LaPrade CM, Foad A, Smith SD, et al. Biomechanical consequences of a nonanatomic posterior medial meniscal root repair. *Am J Sports Med.* 2015;43(4):912-920.
21. Liechti DJ, Constantinescu DS, Ridley TJ, Chahla J, Mitchell JJ, Vap AR. Meniscal repair in pediatric populations: a systematic review of outcomes. *Orthop J Sports Med.* 2019;7(5):2325967119843355.
22. Malinowski K, Góralczyk A, Hermanowicz K, LaPrade RF. Tips and pearls for all-inside medial meniscus repair. *Arthrosc Tech.* 2019;8(2):e131-e139.
23. Marigi EM, Till SE, Wasserburger JN, Reinholz AK, Krych AJ, Stuart MJ. Inside-out approach to meniscus repair: still the gold standard? *Curr Rev Musculoskelet Med.* 2022;15(4):244-251.
24. Masferrer-Pino A, Saenz-Navarro I, Rojas G, et al. The menisco-tibio-popliteus-fibular complex: anatomic description of the structures that

- could avoid lateral meniscal extrusion. *Arthroscopy*. 2020;36(7):1917-1925.
25. Masoudi A, Beamer BS, Harlow ER, et al. Biomechanical evaluation of an all-inside suture-based device for repairing longitudinal meniscal tears. *Arthroscopy*. 2015;31(3):428-434.
 26. Owens BD. The gold standard. *Am J Sports Med*. 2023;51(3):577-578.
 27. 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(7):2325967120936672.
 28. Paxton ES, Stock MV, Brophy RH. Meniscal repair versus partial meniscectomy: a systematic review comparing reoperation rates and clinical outcomes. *Arthroscopy*. 2011;27(9):1275-1288.
 29. Peltier A, Lording T, Maubisson L, Ballis R, Neyret P, Lustig S. The role of the meniscotibial ligament in posteromedial rotational knee stability. *Knee Surg Sports Traumatol Arthrosc*. 2015;23(10):2967-2973.
 30. Rangger C, Klestil T, Gloetzer W, Kemmler G, Benedetto KP. Osteoarthritis after arthroscopic partial meniscectomy. *Am J Sports Med*. 1995;23(2):240-244.
 31. Smith HE, Lyons MM, Patel NM. Epidemiology of meniscal allograft transplantation at children's hospitals in the United States. *Orthop J Sports Med*. 2021;9(9):23259671211034877.
 32. Tagliero AJ, Desai VS, Kennedy NI, et al. Seventeen-year follow-up after meniscal repair with concomitant anterior cruciate ligament reconstruction in a pediatric and adolescent population. *Am J Sports Med*. 2018;46(14):3361-3367.
 33. Tagliero AJ, Kennedy NI, Leland DP, et al. Meniscus repairs in the adolescent population—safe and reliable outcomes: a systematic review. *Knee Surg Sports Traumatol Arthrosc*. 2020;28(11):3587-3596.
 34. Tsujii A, Nakamura N, Horibe S. Age-related changes in the knee meniscus. *Knee*. 2017;24(6):1262-1270.
 35. van der List JP, Flanigan DC. Editorial commentary: repair of radial meniscus tears. *Arthroscopy*. 2024;41(5):1680-1682.
 36. Vint H, Quartley M, Robinson JR. All-inside versus inside-out meniscal repair: a systematic review and meta-analysis. *Knee*. 2021;28:326-337.
 37. Vuong B, Segovia N, Randhawa S, et al. Growth of the pediatric knee meniscus: a cadaveric study. *Orthop J Sports Med*. 2020;8(7)(suppl 6):2325967120S00445.
 38. Yeh SH, Hsu FW, Chen KH, Chiang ER, Chang MC, Ma HL. Repairing complete radial tears of the lateral meniscus: arthroscopic all-inside double vertical cross-suture technique is effective and safe with 2-year minimum follow-up. *Arthroscopy*. 2022;38(6):1919-1929.