

Lateral meniscal positional asymmetry during early knee flexion under axial loading following anterior cruciate ligament reconstruction: a paired-knee MRI study

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Abstract

Meniscal responses during early flexion under axial loading after anterior cruciate ligament reconstruction (ACLR) remain unclear. We performed paired magnetic resonance imaging (MRI) with three-dimensional reconstruction in 14 men with unilateral ACLR at unloaded 0° and under axial loading at 0°, 15°, and 30°. The unloaded state served as the reference. Whole-meniscus position was quantified by anteroposterior and mediolateral displacement of the center of the best-fit circle fitted to the two-dimensional projected outer contour. Regional outcomes were mean positive and mean negative surface deviations and change in radial meniscal extrusion along fixed reference lines. Holm correction was applied within each outcome family. Compared with the contralateral knee (CON knee), the lateral meniscus in the ACLR-reconstructed knee (ACLR knee) showed greater posterior change by 0.88, 1.67, and 2.01 mm at 0°, 15°, and 30° (Holm-adjusted $P = 0.0012$, 0.0012 , and < 0.0001 , respectively). It also showed greater lateral change by 1.46 and 1.43 mm at 15° and 30° (Holm-adjusted $P = 0.0012$ and 0.0003). No adjusted side-to-side differences were detected for medial meniscal displacement, regional surface deviations, or radial extrusion changes. These findings indicate asymmetry in lateral meniscal position after ACLR and suggest that altered knee kinematics may affect the meniscus.

Introduction

The menisci distribute load and contribute to knee stability, while their tissue and attachments show direction- and region-dependent mechanical behavior [1–3]. Cadaveric studies of anterior cruciate ligament (ACL)-deficient knees also indicate distinct stabilizing roles for the medial and lateral menisci under different loading conditions [4, 5]. Meniscal behavior after ACL injury and reconstruction therefore cannot be inferred from static morphology or osseous stability alone.

Although anterior cruciate ligament reconstruction (ACLR) aims to restore knee stability, tibiofemoral kinematics and cartilage contact may remain altered, depending on loading and activity [6–9]. Postoperative imaging studies have largely examined bone motion or cartilage contact rather than direct meniscal responses. Magnetic resonance imaging (MRI) studies have characterized meniscal motion across flexion in healthy and ACL-deficient knees [10–12], and Liu et al. quantified load-dependent changes during early knee flexion in healthy knees using MRI and three-dimensional (3D) comparisons [13]. Existing morphometric methods and tibial coordinate systems permit anatomically standardized comparisons across conditions and regions [14–16].

The unresolved question is therefore not whether menisci move during loading, but whether an ACLR-reconstructed knee shows side-to-side asymmetry in whole-meniscus position and, if so, whether this asymmetry is accompanied by regional geometric differences. A bilateral paired design can separate these outcome families while reducing between-participant anatomical variability.

We addressed this question using bilateral paired MRI in individuals with unilateral ACLR. For each knee, the unloaded 0° condition (0U) served as the reference for axial loading at 0°, 15°, and 30° (0L, 15L, and 30L). We compared the ACLR-reconstructed knee (ACLR knee) with the contralateral knee (CON knee) for

the medial meniscus (MM) and lateral meniscus (LM). The three outcome families were whole-meniscus anteroposterior (AP) and mediolateral (ML) displacement, mean positive and mean negative surface deviations after rigid best-fit registration, and change in radial meniscal extrusion along fixed lines defined in the reference configuration. This exploratory study tested whether whole-meniscus positional asymmetry during early flexion under axial loading was accompanied by regional geometric differences.

Methods

Subjects

This single-center, cross-sectional exploratory imaging study used a within-participant bilateral paired design. Eligibility criteria were age 18–45 years, at least 6 months after ACLR, skeletal maturity, and ability to complete MRI under axial loading. Participants also had no clinically evident knee pain or instability. Exclusion criteria were a body mass index of at least 30 kg/m², congenital meniscal dysplasia, meniscal lesions and related surgeries, a preoperative pivot-shift test grade of ≥ 2 , or diffuse cartilage injury.

The study was approved by the Institutional Review Board Ethics Committee of China-Japan Union Hospital of Jilin University (IRB No. 2022-KYYS-052). Informed consent was obtained from each of the individual participant included in this study in accordance with the Helsinki Declaration.

Two experienced orthopedic surgeons confirmed the absence of meniscal injury in both knees during screening. For the ACLR knee, this assessment combined preoperative MRI with operative records. The records documented no intraoperative meniscal injury and no meniscal repair, resection, or other meniscal procedure. The opposite healthy knee was defined as the CON knee.

MRI scanning

Imaging was performed on a 3.0-T MRI system (Siemens Healthineers, Erlangen, Germany) using a body 18-channel soft coil (Siemens Healthcare GmbH, Erlangen, Germany). An MRI-compatible device provided axial loading during loaded scans. All scans used a T2-weighted double-echo steady-state sequence with water excitation. The echo time was 5.0 ms, and the repetition time was 14.8 ms. The field of view was 14 cm, with a 256 × 240 matrix, 0.6-mm slice thickness, one excitation, and a 4.0-min acquisition time.

Each knee was scanned in four conditions, giving eight scans per participant. These conditions were unloaded at 0° (0U) and under axial loading at 0° (0L), 15° (15L), and 30° (30L). Thus, 0L–0U represented the change under axial loading at full extension. The 15L–0U and 30L–0U differences combined axial loading with flexion and did not isolate angle-matched effects of axial loading. Before the first scan, participants rested supine without axial loading for 15 min. Between scans, they rested supine without axial loading for 15 min to minimize carryover deformation from the preceding condition. Participants lay

supine in a custom MRI-compatible lower-limb loading device, with both knees initially fully extended. Individually fabricated polymer splints maintained knee flexion at 0°, 15°, or 30°.

Before each scan, sagittal localizer images confirmed the flexion angle using the angle between the tibial and femoral midlines. During axial loading, a ratchet system applied an axial force equal to 50% of body weight to the tested leg. A load sensor connected to a digital display was used to monitor and maintain the target force. Shoulder and waist straps limited trunk motion (Fig. 1) (Written informed consent was obtained from the participant shown in Fig. 1 for publication of their photograph in an online open-access publication.).

Image analyses

Scan data were stored in Digital Imaging and Communications in Medicine (DICOM) format and imported into Mimics 21.0 (Materialise, Belgium). Two experienced orthopedic surgeons (M.K.Y. and J.S.T.) independently segmented the tibia, MM, and LM using the same threshold-based workflow. Limited smoothing was applied to refine the 3D models. For every scan, tibial reconstruction extended from the tibial plateau to 60 mm distally. Both surgeons independently segmented and measured all models using the same predefined workflow.

Tibial registration and regional surface-deviation analysis

All eight 3D knee models from each participant were imported into Geomagic Control X 2020.1 (Geomagic, Research Triangle Park, NC, USA). 3D comparisons followed our previously established method [13]. For each knee, the 0U model served as the fixed reference, and the 0L, 15L, and 30L models were comparison models. Rigid registration used the tibial segment from the plateau to 60 mm distally in both the reference and comparison models. The same registration procedure was applied to every model and accepted only after manual review confirmed satisfactory alignment. The resulting rotation and translation matrix was applied to the corresponding MM and LM. This preserved the tibia–meniscus spatial relationship. Scaling, reflection, and non-rigid deformation were not permitted.

For regional surface-deviation analysis, each comparison-state meniscus was then rigidly best-fit to its corresponding 0U meniscus. This step separated residual surface geometry from whole-meniscus position. Signed surface deviations were defined relative to the local normals of the 0U reference surface. Positive values followed the positive local-normal direction, whereas negative values followed the opposite direction.

Regional analyses followed Shen et al. [17]. The anterior horn (AH), body (BD), and posterior horn (PH) were defined using the covering angle (CA) on the two-dimensional (2D) projection. The CA had its vertex at the best-fit-circle center and was bounded by two anatomical lines. For the LM, the lines passed through the most medial points of the AH and PH. For the MM, they passed through the most lateral

points. The entire CA was divided into three equal angular sectors, assigned from anterior to posterior as AH, BD, and PH.

Whole-meniscus displacement

Registered models were exported in stereolithography (STL) format and imported into 3-matic Research 13.0 (Materialise, Leuven, Belgium). For each 0U tibial plateau, 50 points were randomly selected from the candidate articular-surface region of each compartment, giving 100 points per knee. These 100 points defined the best-fit plane. The 0U and comparison-state menisci were orthogonally projected onto the corresponding plane. The center of the best-fit circle fitted to the 2D projected outer contour represented meniscal position in that plane.

The posterior tibial condylar line (PTCL) defined the ML axis, and its perpendicular defined the AP axis. Lateral and anterior directions were positive. Whole-meniscus displacement was the signed difference between the comparison-state and 0U circle-center coordinates along the AP and ML axes [13] (Fig. 2).

Regional changes in radial meniscal extrusion

Regional changes were quantified as the change in radial meniscal extrusion measured along fixed lines defined in the reference configuration [13,17,18]. The 0U best-fit-circle center was the origin for every condition. For the AH, BD, and PH, the measurement line was the angular bisector of the corresponding CA sector. Each reference line retained the same origin and direction across all conditions. Along each line, the radial distance from the 0U origin to the projected outer contour was measured for 0U and each comparison state. Change was calculated as the comparison-state distance minus the 0U distance. Positive values indicated outward change, and negative values indicated inward change along the fixed line. This metric represented relative radial change and not absolute extrusion beyond the tibial margin.

Statistical analysis

Statistical analyses were performed using IBM SPSS Statistics 25.0 (IBM Corp., Armonk, NY, USA). The participant was the independent analysis unit, while within-participant pairing across knees and conditions was retained. Continuous variables are reported as mean $\pm$ standard deviation. Analyses included 14 participants with complete measurements. The average of the measurements taken by the two surgeons was used for the primary analysis.

Primary analyses compared the ACLR and CON knees for the same meniscus, region, and outcome at 0L, 15L, and 30L. Paired differences were defined as the ACLR-knee value minus the CON-knee value. The distribution of each paired difference was evaluated using the Shapiro–Wilk test and Q–Q plots. A two-sided paired t test was used when the Shapiro–Wilk P value was at least 0.05. Otherwise, a two-

sided exact Wilcoxon signed-rank test was used. Distributional assumptions required for a location-shift interpretation of Wilcoxon results were also assessed. Paired differences were retained to eight decimal places before testing to reduce floating-point effects on tied ranks. Wilcoxon tests excluded zero differences and assigned average ranks to tied absolute differences. As a sensitivity analysis, displacement comparisons were reanalyzed using exact Wilcoxon signed-rank tests.

The Holm step-down procedure controlled multiplicity separately within three primary outcome families [19]. These comprised 12 whole-meniscus displacement, 36 regional surface-deviation, and 18 regional radial-extrusion comparisons. Raw and Holm-adjusted P values were reported. The 0U condition was the reference for changes. Interpretation of early-flexion changes under axial loading focused on comparisons among 0L, 15L, and 30L.

Within-knee comparisons among 0U, 0L, 15L, and 30L were supplementary exploratory analyses. Exact Friedman omnibus tests were applied to each combination of side, meniscus, region, and outcome. Pairwise comparisons followed the testing rules described above. The intraclass correlation coefficient (ICC) was evaluated by a one-way random effects model to quantify interobserver and intraobserver reliability of the extrusion and displacement measurements to assess the reproducibility. Statistical significance within each family was defined as a Holm-adjusted $P \leq 0.05$.

Results

Fourteen participants with unilateral ACLR were included. Their mean age was 32.1 ± 7.2 years, and their mean body mass index was 25.8 ± 2.3 kg/m². The mean postoperative interval was 22.0 ± 11.3 months (range, 9–50 months). The ACLR knee was the left knee in eight participants and the right knee in six (Table 1). All changes were calculated from the within-knee unloaded 0° reference condition (0U). The 0L, 15L, and 30L states denote axial loading at 0°, 15°, and 30°, respectively. Representative surface-deviation maps from one participant are shown in Fig. 3.

Compared with the CON knee, the LM in the ACLR knee showed greater posterior displacement at 0L, 15L, and 30L. Paired differences were calculated as the ACLR knee minus the CON knee. The AP differences were -0.88 , -1.67 , and -2.01 mm, respectively (Holm-adjusted $P = 0.0012$, 0.0012 , and <0.0001). At 15L and 30L, the LM also showed greater lateral displacement, with ML differences of 1.46 and 1.43 mm, respectively. The corresponding Holm-adjusted P values were 0.0012 and 0.0003 . At 0L, the ML difference was 0.95 mm and was not statistically significant after correction (Holm-adjusted $P = 0.4322$). For each of the five statistically significant comparisons, all 14 participant-level differences were in the same direction.

For the MM, mean AP displacement became more posterior in both knees as flexion increased under axial loading. At 30L, mean AP displacement was -1.12 mm in the ACLR knee and -1.43 mm in the CON knee. Mean ML displacement was medial at every state in the CON knee. In the ACLR knee, it was slightly lateral at 0L and 15L but medial at 30L. None of the six side-to-side comparisons was statistically significant after Holm adjustment (all adjusted $P = 1.0000$). Group means, standard

deviations, and CIs for paired differences are reported in Table 2, and displacement trajectories are shown in Fig. 4.

After rigid best-fit registration of each meniscus, no Holm-adjusted side-to-side differences were detected in regional surface deviations. This analysis covered the AH, BD, and PH of both menisci (36 comparisons; all Holm-adjusted $P \geq 0.5152$). Descriptively, mean positive surface deviations increased with flexion across all three MM regions in the ACLR knee. For the LM, the absolute mean negative surface deviations increased with flexion in all three regions of both knees. These deviations were more negative in the ACLR knee than in the CON knee at every state under axial loading. These descriptive patterns are shown in Fig. 5 and Supplementary Tables S1 and S2.

Relative to 0U, mean MM radial changes became increasingly inward at the AH and outward at the PH from 0L to 30L in both knees. At 30L, AH changes were -1.24 and -1.70 mm, and PH changes were 1.24 and 1.08 mm in ACLR and CON knees, respectively. LM AH changes shifted from outward at 0L to inward at 15L and 30L, reaching -5.98 and -5.10 mm at 30L. LM PH changes increased across loaded states, reaching 3.96 and 3.87 mm, respectively. BD changes were smaller and ranged from -1.01 to 0.24 mm across both knees and all loaded states. None of the comparisons was significant after Holm adjustment (all adjusted $P = 1.0000$; Fig. 6 and Supplementary Table S3).

Within-knee comparisons identified changes between loaded states (Supplementary Table S4). From 0L to 30L, LM AP displacement changed by -4.71 mm in ACLR knees and -3.58 mm in CON knees (Holm-adjusted $P < 0.0001$ and $P = 0.0001$, respectively). MM AP displacement also became more posterior in CON knees (-1.26 mm; adjusted $P = 0.0425$). LM AH radial changes decreased from 0L to 15L and 30L in both knees, with differences ranging from -6.67 to -4.65 mm (all adjusted $P \leq 0.0006$). LM PH radial changes increased from 0L to 30L in ACLR knees and from 0L to 15L and 30L in CON knees. These differences ranged from 3.57 to 4.05 mm (all adjusted $P \leq 0.0127$). In ACLR knees, LM mean positive surface deviations increased in the BD from 0L to 15L and 30L and in the PH from 0L to 15L. These increases ranged from 0.18 to 0.20 mm (all adjusted $P \leq 0.0302$). LM mean negative surface deviations became more negative from 0L to 30L in the AH (-0.26 mm; adjusted $P = 0.0112$) and PH (-0.17 mm; adjusted $P = 0.0068$).

The exact Wilcoxon sensitivity analysis retained the same five statistically significant whole-meniscus displacement outcomes for the LM (Supplementary Table S5). Intraclass correlation coefficient results of the intraobserver and interobserver reliabilities were both > 0.75 , which were in the excellent range (Supplementary Table S6).

Discussion

Side-to-side differences after ACLR were confined to whole-meniscus position of the LM. The ACLR knee showed greater posterior change at 0° , 15° , and 30° under axial loading and greater lateral change at 15° and 30° , whereas no Holm-adjusted differences were detected for MM displacement, regional surface deviations, or radial extrusion changes. Taken together, these findings indicate an asymmetry in whole-

LM positional response under the tested conditions, without evidence of a corresponding side-to-side difference in regional surface geometry or radial extrusion. The distinction is important: displacement of the fitted-circle center describes translation of the projected meniscal contour and should not be interpreted as local extrusion or tissue deformation.

Posterior meniscal movement during early flexion occurred in both knees, and the principal finding was the difference in its magnitude between knees. Liu et al. reported generally posterior and lateral meniscal movement during early flexion in healthy knees [13], whereas Vedi et al. and Yamamoto et al. showed that meniscal motion varies with region, loading, and flexion angle [10, 11]. Our posterior patterns were directionally consistent with these studies, but the MM did not show uniform lateral movement. Only 0L-0U isolated the effect of axial loading at a matched angle; 15L-0U and 30L-0U combined flexion and loading. Accordingly, the present data define a side-specific response over combined loading and early flexion rather than a pure flexion effect or a pure loading effect at 15° and 30°.

Residual tibiofemoral kinematics or altered femoromeniscal contact may contribute to the LM positional asymmetry. Previous in vivo studies documented activity- and loading-dependent rotational or compartment-specific kinematic differences after ACLR [6–8], together with residual cartilage-contact abnormalities at low flexion angles [9]. In a dynamic cadaveric model, ACL deficiency increased anterior tibial translation and internal rotation and produced additional posterior LM translation [20], providing directional biomechanical context for our finding but not a direct postoperative comparison. In reconstructed knees, incomplete recovery may arise from graft orientation, tunnel position, tension, maturation, or elongation.

The anterolateral soft-tissue complex includes the anterolateral ligament (ALL), iliotibial band, and anterolateral capsule. These structures contribute to restraint of tibial internal rotation and anterolateral rotatory instability [21, 22]. Anterolateral ligament reconstruction (ALLR) and lateral extra-articular tenodesis (LET) are distinct procedures intended to augment rotational stability alongside ACLR. Getgood et al. reported that adding LET to hamstring-autograft ACLR reduced two-year composite clinical failure in young, high-risk patients [23]. Combined ACLR and ALLR also improved pivot-shift and instrumented-laxity findings in male athletes with high-grade pivot shift [24]. In the present study, the ACLR knee showed greater posterior LM displacement under axial loading and greater lateral displacement at 15° and 30°. These differences may reflect altered tibiofemoral motion patterns. Together with the established role of the anterolateral complex, our findings provide further rationale for investigating ALLR and LET as potential approaches to improving postoperative meniscal displacement.

Change in radial meniscal extrusion quantified the difference in radial distance between 0U and each comparison state along fixed reference rays. This relative measure is conceptually similar to absolute meniscal extrusion beyond the tibial margin. Greater absolute medial meniscal extrusion has been associated with incident radiographic knee osteoarthritis [25]. In the present study, no statistically significant side-to-side differences in radial meniscal extrusion changes were detected after Holm

adjustment. Thus, this further demonstrates the protective effect of ACLR on the meniscus. Rigid best-fit registration removed translation and rotation. The combination of significant whole-LM displacement with nonsignificant regional surface-deviation and extrusion comparisons is consequently more consistent with altered global meniscal tracking than with proven local structural failure.

Several limitations define the scope of these inferences. The sample comprised 14 men with postoperative intervals of 9–50 months, limiting generalizability and preventing separation of body size, postoperative stage, and surgical factors. Bilateral pairing reduces between-participant variability, but CON knees may adapt after unilateral ACLR [26], and the cross-sectional design lacks preoperative three-dimensional imaging and an independent healthy control group. No single primary endpoint was prespecified; Holm adjustment was confined to each outcome family; CIs were not used to assess equivalence. The next discriminating study should combine the same loaded meniscal measurements with femoral and tibial models to quantify six-degree-of-freedom tibiofemoral kinematics, while also recording quantitative pivot shift, graft and tunnel geometry, anterolateral-complex and meniscal-root status, posterior tibial slope, hyperextension, and generalized ligamentous laxity. Longitudinal cartilage-composition imaging would then test whether persistent LM tracking asymmetry precedes altered contact mechanics or matrix change.

Conclusion

In this bilateral paired MRI study, the ACLR knee showed greater posterior LM positional change than the CON knee under axial loading at 0°, 15°, and 30°. Greater lateral change was also detected at 15° and 30°. After Holm adjustment, no statistically significant side-to-side differences were detected in MM displacement, regional surface deviations, or radial extrusion changes in either meniscus. These findings identify side-to-side asymmetry in the whole-meniscus positional response of the LM. They provide a rationale for investigating whether ALLR and LET can improve postoperative meniscal displacement patterns. These discoveries may also inform future assessments of functional recovery after ACLR and indirectly demonstrate that ACLR has a protective effect on the meniscus. Future studies should examine additional factors influencing postoperative meniscal responses and determine their relationships with knee function.

Declarations

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Author contributions

M.K.Y. and T.L. conceived the study. M.K.Y. and J.L.D. drafted the manuscript and prepared the figures. J.S. T., X.D.W., R.Y.N., H.H.G. and X.H.S. collected the data and prepared the tables. J.L.Z.

provided critical comments. All authors discussed the results, revised the manuscript, and approved the final version.

Competing interests

The authors declare no competing interests.

Data Availability

Names, dates of birth, and raw identifiable medical information are not included in publicly available materials. Data supporting the findings may be shared under controlled access upon reasonable request to T.L.

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Tables

Table 1. Participant characteristics

Variable	Value
Age at MRI, years	32.1 ± 7.2 (18.2–42.5)
Sex	Male, 14 (100%)
BMI, kg/m ²	25.8 ± 2.3 (22.0–29.7)
Weight, kg	80.5 ± 9.7 (62.0–95.0)
ACL-reconstructed side	Left, 8; right, 6
Postoperative interval, months	22.0 ± 11.3 (9–50)
MRI examination dates	1 February to 14 March 2026

Values are mean ± standard deviation (range). BMI, body mass index; MRI, magnetic resonance imaging.

Table 2. Paired side-to-side comparisons of whole-meniscus displacement

Meniscus	State	Axis	ACLR knee	CON knee	Δ [95% CI]	Raw P	Holm-adjusted P
MM	0L	AP	-0.3501 $\pm$ 0.8324	-0.1662 $\pm$ 1.1018	-0.1838 [-0.6180, 0.2566]	0.4433	1.0000
MM	0L	ML	0.0836 $\pm$ 1.6820	-0.2277 $\pm$ 1.1694	0.3113 [-0.8171, 1.6100]	0.7609	1.0000
MM	15L	AP	-0.9717 $\pm$ 1.5272	-0.6999 $\pm$ 1.3087	-0.2718 [-1.3524, 0.7429]	0.6370	1.0000
MM	15L	ML	0.2149 $\pm$ 1.9718	-0.5583 $\pm$ 1.4175	0.7731 [-0.2728, 1.8057]	0.1840	1.0000
MM	30L	AP	-1.1162 $\pm$ 1.4241	-1.4253 $\pm$ 1.1168	0.3090 [-0.6682, 1.3103]	0.5665	1.0000
MM	30L	ML	-0.7023 $\pm$ 1.9989	-0.8219 $\pm$ 2.3609	0.1196 [-1.4400, 1.7143]	0.8886	1.0000
LM	0L	AP	-0.5776 $\pm$ 1.0634	0.3044 $\pm$ 1.0778	-0.8820 [-1.2191, -0.6037]	0.0001	0.0012*
LM	0L	ML	-0.0582 $\pm$ 0.9416	-1.0046 $\pm$ 1.2316	0.9464 [0.1042, 1.8750]	0.0617	0.4322
LM	15L	AP	-4.8188 $\pm$ 1.7876	-3.1495 $\pm$ 1.8500	-1.6693 [-2.4414, -1.0175]	0.0001	0.0012*
LM	15L	ML	0.8247 $\pm$ 1.3365	-0.6378 $\pm$ 1.3539	1.4625 [0.9728, 1.9946]	0.0001	0.0012*
LM	30L	AP	-5.2879 $\pm$ 1.8764	-3.2753 $\pm$ 1.7076	-2.0126 [-2.3315, -1.6485]	<0.0001	<0.0001*
LM	30L	ML	1.3519 $\pm$ 1.4367	-0.0778 $\pm$ 1.2967	1.4298 [1.0111, 1.8678]	<0.0001	0.0003*

Each comparison included 14 participants. ACLR-knee and CON-knee values are mean $\pm$ standard deviation in millimeters. Δ is the ACLR-knee value minus the CON-knee value; 95% confidence intervals are unadjusted percentile intervals for the paired mean difference.

AP values are positive anteriorly and negative posteriorly; ML values are positive laterally and negative medially. Holm adjustment was applied across the 12 whole-meniscus displacement comparisons.

*Holm-adjusted $P < 0.05$.

ACLR knee, ACL-reconstructed knee; CON knee, contralateral knee; MM, medial meniscus; LM, lateral meniscus; AP, anteroposterior; ML, mediolateral; CI, confidence interval.

Figures

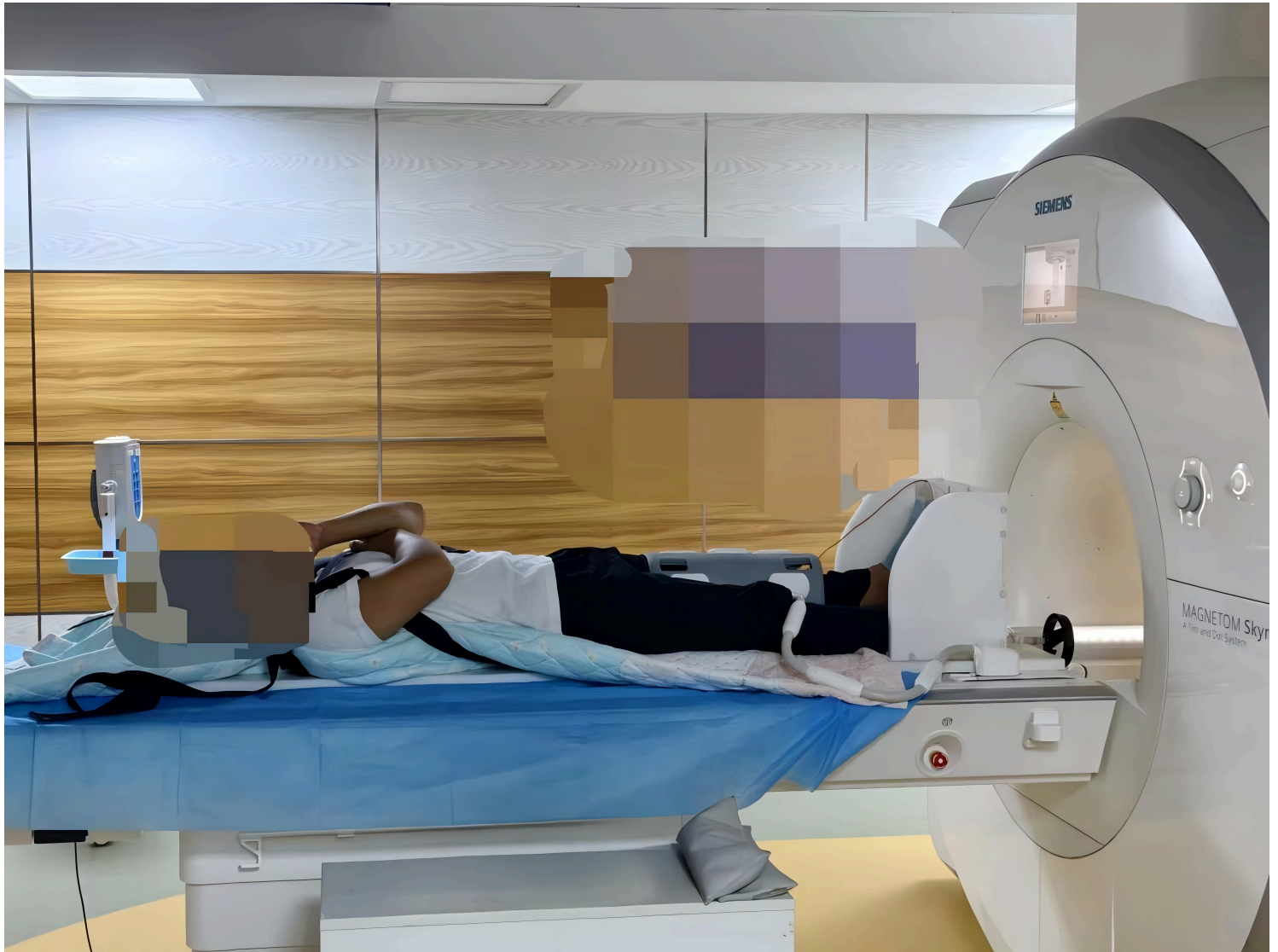
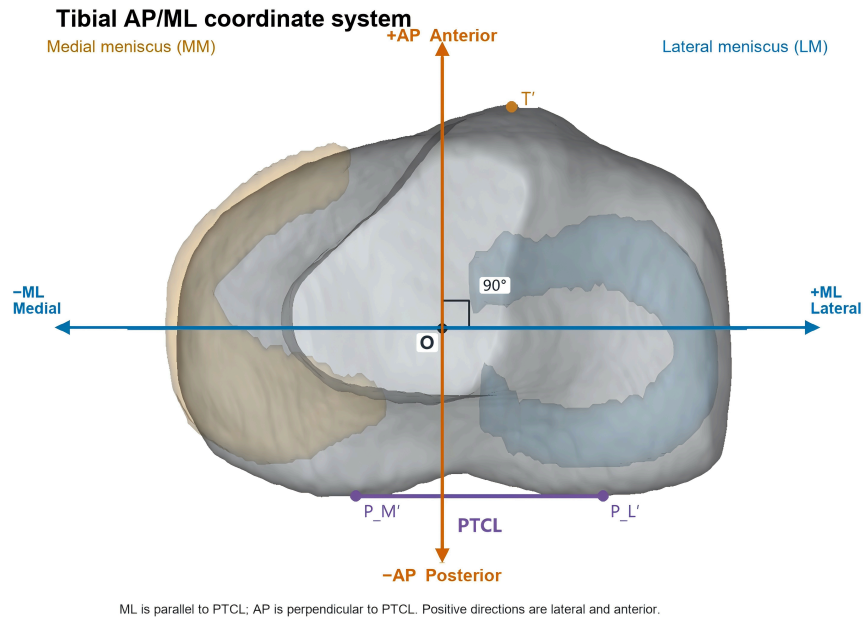


Figure 1

MRI-compatible device for axial loading and participant positioning. The ratchet system applied 50% of body weight to the tested leg. Straps and a custom polymer splint limited trunk motion and maintained the knee-flexion angle.

a



b Representative whole-meniscus displacement measurement

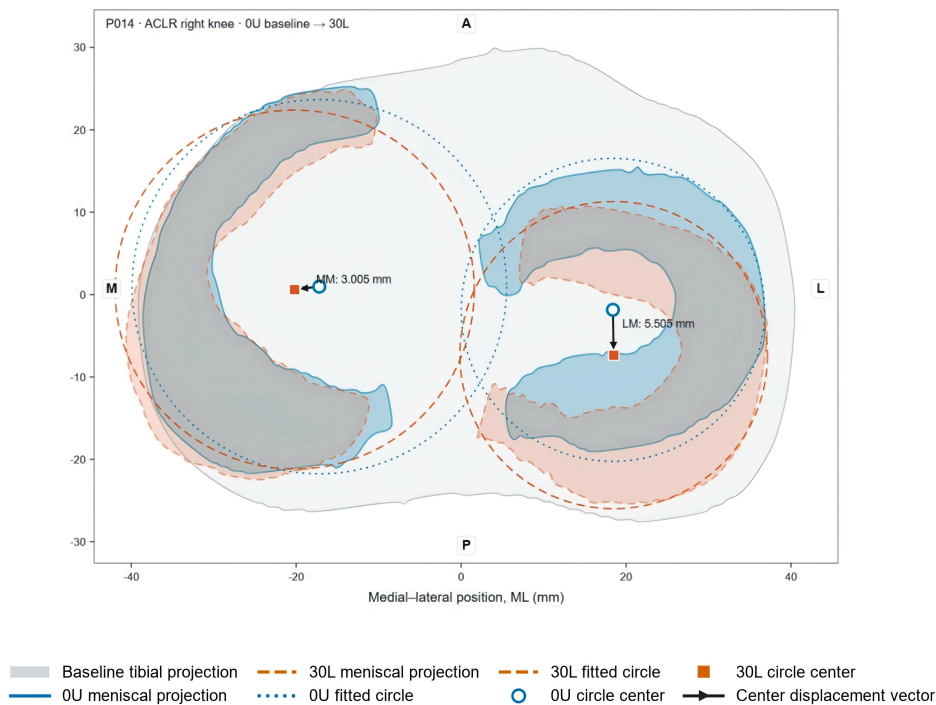


Figure 2

Tibial coordinate system and whole-meniscus displacement measurement. (a) The posterior tibial condylar line (PTCL) defined the mediolateral (ML) axis in the projection plane, and its perpendicular defined the anteroposterior (AP) axis. (b) Arrows show the signed difference between the 0U and comparison-state circle centers. Positive directions are anterior and lateral; the example shows 0U and 30L.

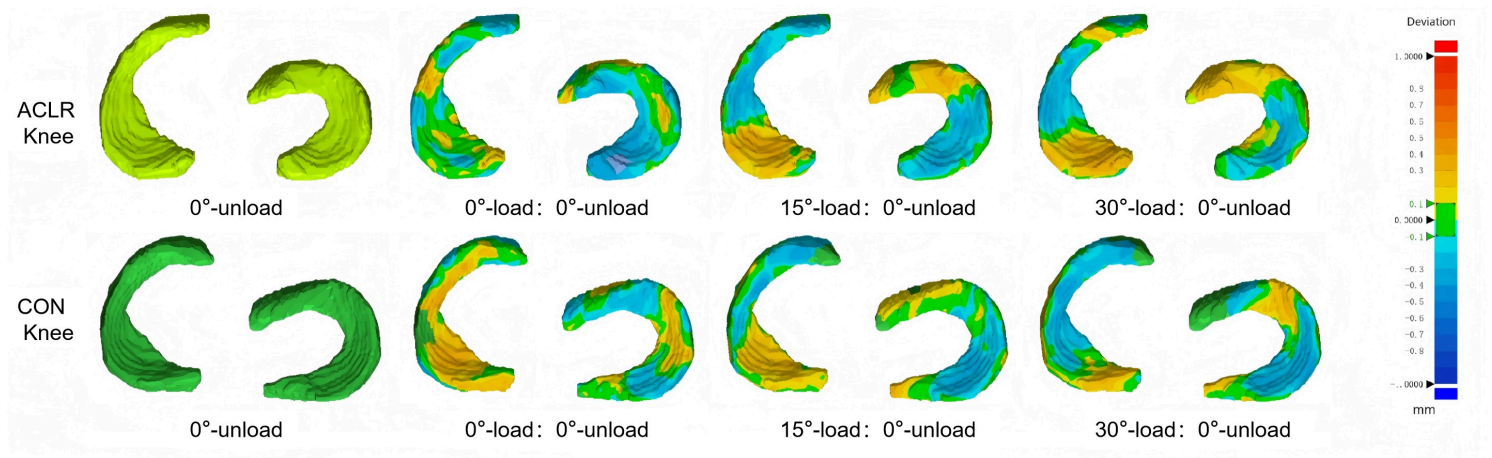


Figure 3

Meniscal surface-deviation maps under axial loading in a representative participant. The unloaded 0° models (0U) serve as the reference configuration. Maps show the ACL-reconstructed knee (ACLR knee) and contralateral knee (CON knee) at 0L, 15L, and 30L relative to 0U. Colors in the 0U column indicate orientation only and do not represent surface-deviation values. The color bar is in millimeters. CON knee images were mirrored for display purposes only.

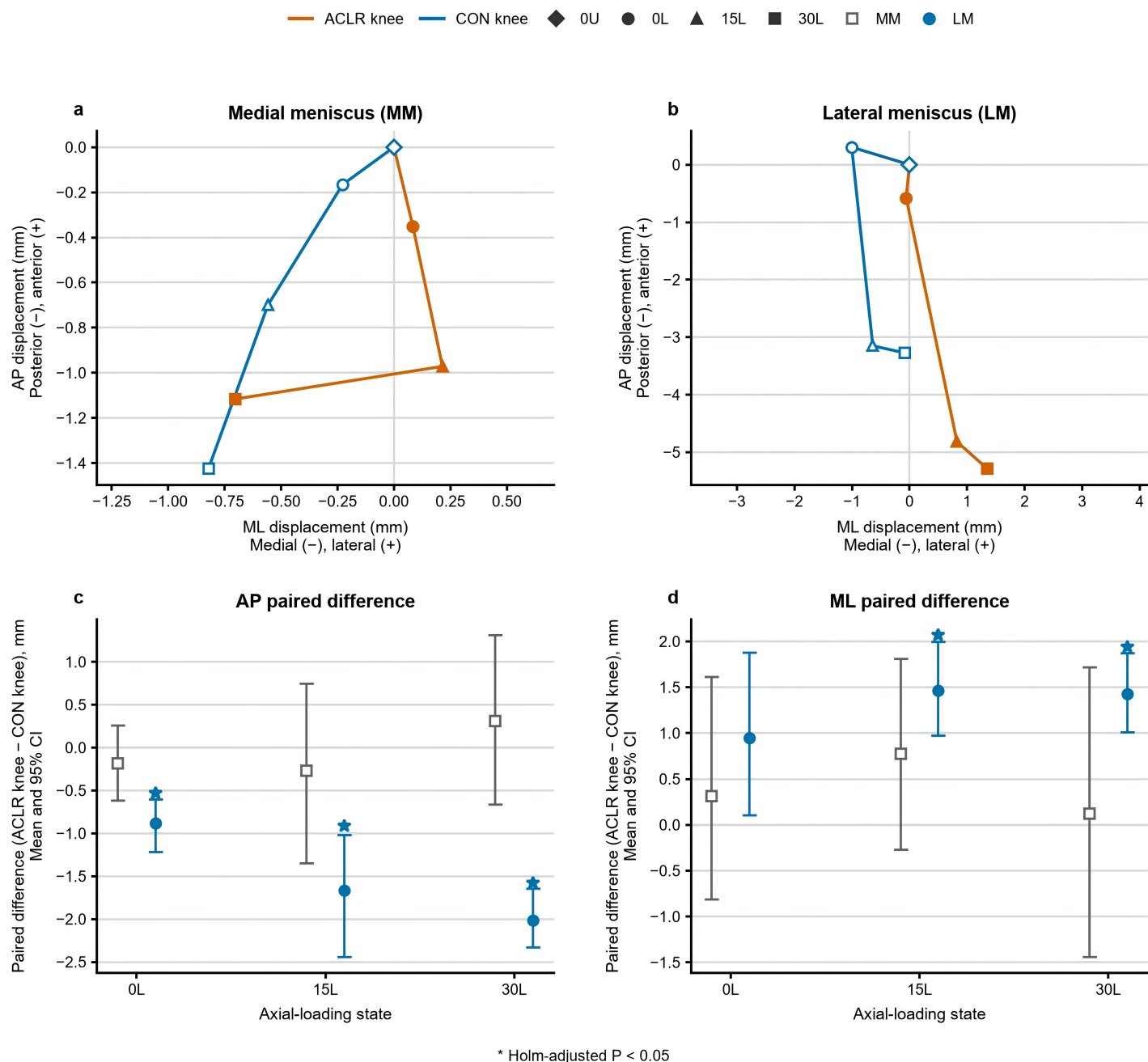


Figure 4

Whole-meniscus anteroposterior and mediolateral displacement and paired side-to-side differences. (a,b) Group-mean displacement paths for the medial meniscus (MM) and lateral meniscus (LM) in the ACL-reconstructed knee (ACLR knee) and contralateral knee (CON knee) from 0U to 0L, 15L, and 30L. (c,d) Paired mean differences for AP and ML displacement. Open squares denote MM and filled circles denote LM. Points and vertical bars show paired mean differences and 95% confidence intervals ($n = 14$). Stars indicate Holm-adjusted $P < 0.05$.

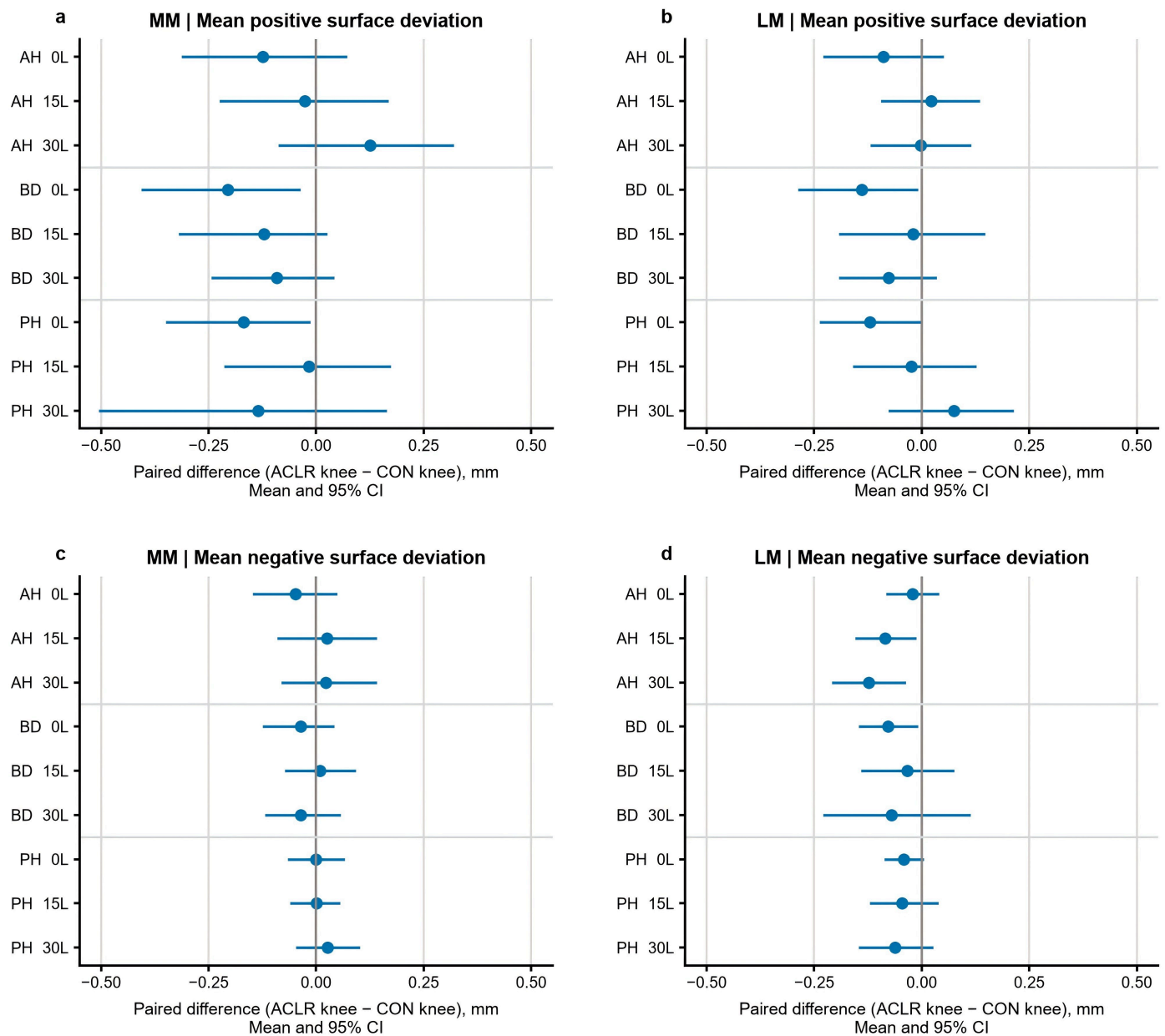


Figure 5

Regional surface deviations after rigid best-fit registration of each meniscus. (a,b) Paired differences in mean positive surface deviations for the medial meniscus (MM) and lateral meniscus (LM). (c,d) Paired differences in mean negative surface deviations. AH, anterior horn; BD, body; PH, posterior horn. Points and horizontal bars show paired mean differences and 95% confidence intervals ($n = 14$). Negative deviations retain their sign; a negative paired difference indicates a greater negative-directed surface distance in the ACL-reconstructed knee.

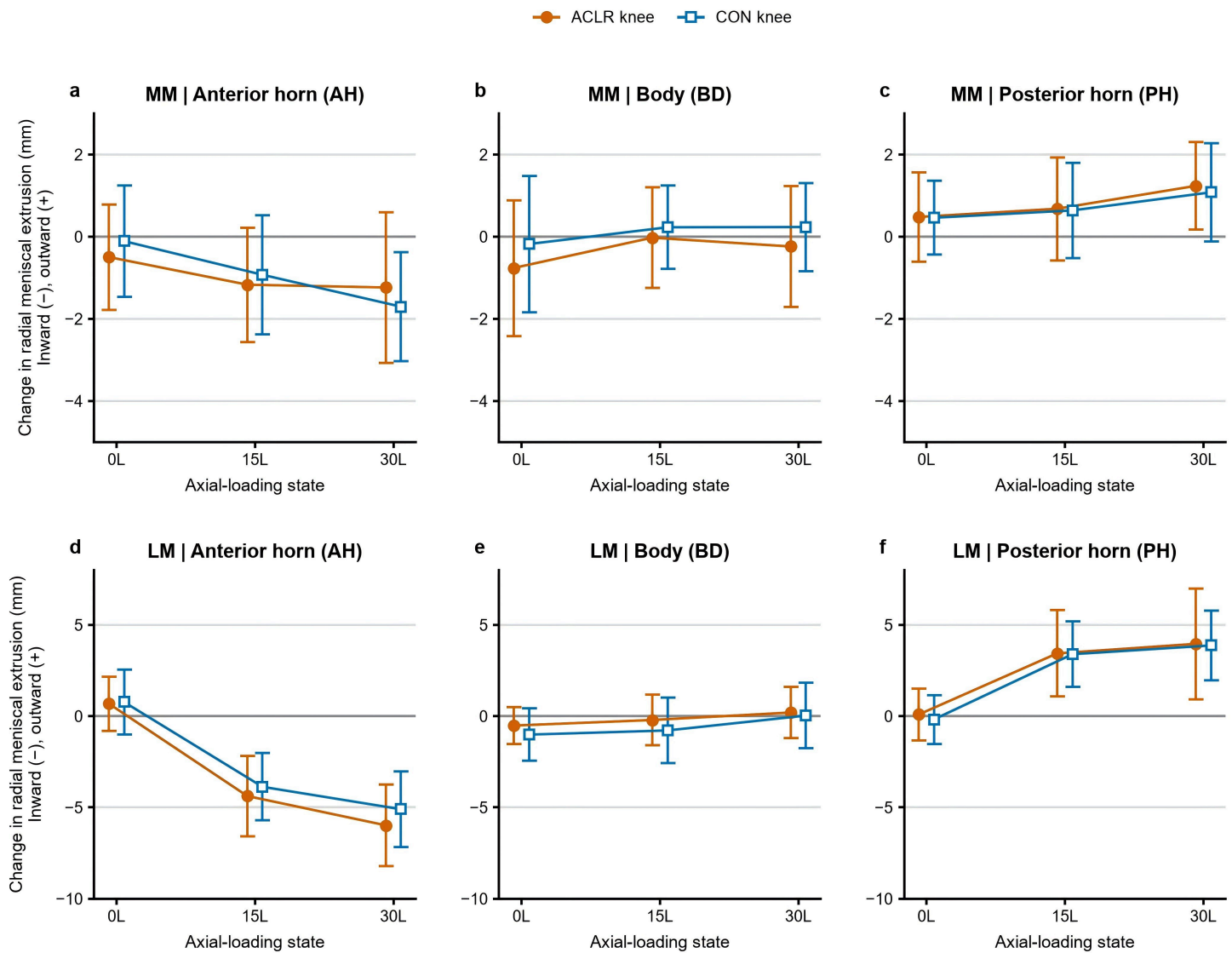


Figure 6

Change in radial meniscal extrusion measured along fixed lines defined in the reference configuration. (a-c) Anterior horn, body, and posterior horn of the medial meniscus (MM). (d-f) Corresponding regions of the lateral meniscus (LM). Points and error bars show mean $\pm$ standard deviation for the ACL-reconstructed knee (ACLR knee) and contralateral knee (CON knee) at 0L, 15L, and 30L ($n = 14$). Positive values indicate outward change, and negative values indicate inward change along the fixed line.

Supplementary Files

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- [Supplementary.docx](#)