

Bony Morphological Characteristics of the Discoid Lateral Meniscus Knee: A Volumetric Magnetic Resonance Imaging-Derived Statistical Shape Modeling Study

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Abstract

Introduction

We sought to characterize the three-dimensional (3D) osseous morphology of the distal femur and proximal tibia in knees with a discoid lateral meniscus (DLM), relative to knees with normal magnetic resonance imaging (MRI) findings, using landmark-based statistical shape modeling of volumetric MRI data.

Methods

We retrospectively analyzed 19 knee MRI scans from 16 patients with symptomatic DLM and 31 scans from 30 age- and sex-matched controls with normal knee MRI findings, all younger than 30 years. Bone surface models were segmented from 3.0-T MRI, and 1003 pseudo-landmarks were placed automatically. Generalized Procrustes analysis and principal component analysis were performed for the femur and tibia combined and for each bone separately. Each principal component (PC) was tested for association with DLM using Firth logistic regression adjusted for age and sex, with patient-clustered standard errors and Holm correction for multiple testing. Tibiofemoral pose and centroid size were compared between groups, and discrimination was estimated by patient-grouped cross-validation.

Results

The mean DLM femur showed a posterior and distal deficit of the lateral femoral condyle with relative prominence of the anterolateral condyle and metaphysis, and the lateral tibial spine was positioned more laterally, widening the intercondylar eminence. In the femur-only model, a single component (PC4, 6.1% of variance) reproduced this femoral pattern and was strongly associated with DLM (odds ratio (OR) per SD 6.43, 95% confidence interval (CI) 3.02-13.73; Holm-adjusted $p < 0.001$). In the combined model, the first two PCs mainly reflected knee flexion and tibial rotation; PC4 (OR 3.31, 95% CI 1.15-9.53) and PC5 (OR 2.62, 95% CI 1.24-5.54), representing tibial intercondylar eminence width and lateral compartment joint space, were associated with DLM but not after Holm correction. No tibial component remained significant after correction. Knee pose and centroid size did not differ between groups. Cross-validated areas under the curve were 0.78 for the combined model and 0.80 for the femur-only model.

Conclusions

In this exploratory study, knees with DLM showed a characteristic posterolateral hypoplasia of the lateral femoral condyle with relative anterolateral prominence, which was associated with DLM independently of age, sex, knee position, and overall size. These hypothesis-generating findings warrant validation in larger cohorts.

Categories: Radiology, Orthopedics

Keywords: bone morphology, discoid lateral meniscus, principal component analysis, statistical shape analysis, three-dimensional magnetic resonance image

Introduction

Discoid lateral meniscus (DLM) is a congenital anomaly characterized by an abnormally shaped, thickened, and often hypermobile lateral meniscus, affecting approximately 0.4-16.6% of the population, predominantly in Asian populations [1]. This condition can lead to several symptoms, including knee pain, clicking, popping, and sometimes locking, and it significantly affects quality of life, especially in young and active individuals [2,3]. Many patients with DLM are asymptomatic, but symptomatic DLM can predispose individuals to meniscal tears, chondral damage, and early-onset osteoarthritis [2,3].

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The diagnosis and characterization of DLM rely primarily on imaging, including plain radiography, computed tomography (CT), and magnetic resonance imaging (MRI). While plain radiographs can occasionally show suggestive findings, such as widening of the lateral joint space [4], MRI is the gold standard for visualizing meniscal anomalies, their extent, and associated articular cartilage or bone changes [5,6]. High-resolution three-dimensional (3D) MRI sequences provide detailed volumetric data that allow comprehensive visualization of knee joint structures, including meniscal and bony morphology. Nevertheless, low sensitivity has been reported for MRI detection of DLM [2,7]. Incomplete discoid menisci can appear normal on MRI, and a torn DLM may be mistaken for a displaced bucket-handle or inverted flap tear [2,7]. Bone morphology may therefore provide complementary information on DLM, although its diagnostic value requires formal evaluation.

Previous studies of DLM have focused mainly on meniscal dimensions, stability, and associated cartilage lesions [5,6], but several have also measured bony features. On radiographs, lateral joint space widening, squaring of the lateral femoral condyle, cupping of the lateral tibial plateau and the condylar cut-off sign have been compared with normal knees [8-11]; in a recent matched case-control study, however, only lateral joint space height and fibular head height differed from normal knees, and radiographs were judged to be of limited diagnostic value [12]. On MRI, hypoplasia of the posterior lateral femoral condyle has been quantified with condylar angles on axial images [4], the lowest point of the lateral femoral condyle has been shown to lie more laterally [13], and the tibial eminence has been reported to be wider, with a lower lateral tibial spine, in complete DLM [14,15]. Findings on the tibial eminence have not been consistent: in a recent MRI study of children and adolescents, tibial eminence width and lateral tibial spine height did not differ between knees with DLM and those with non-discoid lateral meniscal injury [16]. In adults with complete DLM, smaller lateral femoral condyle width and other osseous parameters have been associated with meniscal degeneration and tears [17], suggesting that bone shape may be clinically relevant. These studies, however, measured a limited number of predefined distances and angles on selected radiographs or slices [4,18]. Such measurements depend on slice selection and the observer, and they cannot show how shape differences are distributed across the whole joint surface or whether they co-vary. It therefore remains unknown whether these individual findings form a coherent, region-specific pattern in three dimensions.

Statistical shape analysis (SSA) addresses this by representing each 3D bone surface as a set of corresponding points, from which mean shapes and the dominant axes of inter-subject variability can be derived without predefined measurements [19,20]. SSA has already delineated disease-specific bone shape in other knee disorders, such as patellofemoral instability [21].

The primary aim of this study was to compare the 3D shape of the distal femur and proximal tibia between knees with symptomatic DLM and knees with normal MRI findings in Japanese patients younger than 30 years, using volumetric MRI-derived statistical shape modeling. The secondary aim was to identify shape components associated with DLM after adjustment for age and sex. Because the femur and tibia articulate, we also analyzed each bone separately and estimated knee pose, so that bone shape could be distinguished from positioning during scanning. We hypothesized that DLM knees would show a hypoplastic posterior lateral femoral condyle and a wider tibial intercondylar eminence. As the design is cross-sectional, the study was intended to describe associations, not to establish whether these features are predisposing or adaptive.

Materials And Methods

Participants

The Research Ethics Committee of Saitama Medical University Hospital approved this retrospective study (approval no. 2023-046) and waived the requirement for individual informed consent. The study was conducted in accordance with applicable ethical guidelines.

We screened the records of individuals younger than 30 years who had undergone non-arthrographic knee MRI ordered by the orthopedic department of our institution between January 2017 and September 2021. Patients with a confirmed diagnosis of symptomatic DLM formed the study group. Patients whose symptoms were attributable to other conditions, including fracture, arthritis, chondral injury, osseous stress reaction, or severe ligamentous sprain, were excluded. The control group consisted of age- and sex-matched individuals with normal knee MRI findings and no clinical knee or patellofemoral abnormality; controls with the same conditions were excluded.

DLM was diagnosed on MRI when the width of the lateral meniscal body exceeded 15 mm on coronal images. Two musculoskeletal radiologists assessed all menisci, DLM and control alike, with the same criteria in consensus. Arthroscopic confirmation was available for 10 of 19 DLM knees. The DLM group comprised 13 complete and six incomplete knees, with no Wrisberg-type variant, and a meniscal tear was present in seven knees. The proximal tibial and distal femoral physes were open in two DLM and seven control knees.

The study included 19 MRI scans from 16 patients with DLM (seven male (44%), nine female (56%); age, 20.5 ± 5.3 years (mean ± standard deviation (SD)); seven right side (37%), 12 left side (63%), including both knees of three patients) and 31 scans from 30 controls (13 male (42%), 18 female (58%); age, 20.5 ± 3.9 years; 16 right side (52%), 15 left side (48%), including both knees of one patient). All participants were Japanese. The

cohort is identical to that of our previous volumetric study of articular cartilage and epiphyseal bone in DLM [22]; the present analysis applies an independent statistical shape modeling framework to the bone surfaces and addresses a different question, namely bony contour morphology.

MRI acquisition

Imaging was performed on a 3.0-T scanner (Ingenia Elition X, Philips Healthcare, Best, the Netherlands; software release 5.6.1) with a dedicated 16-channel knee coil. In every subject, a volumetric 3D T2*-weighted multi-echo fast-field echo (mFFE) sequence, optimized for cartilage but also providing clear bone contours, was acquired with the following parameters: repetition time/echo time, 20/7 ms; flip angle, 35°; field of view, 150 × 150 mm; acquisition matrix, 256 × 256 (acquired in-plane resolution, 0.59 × 0.59 mm); receiver bandwidth, 217 Hz/pixel. Images were reconstructed in the axial, sagittal, and coronal planes as 1.5-mm contiguous sections with a 1024 × 1024 matrix (pixel size, 0.15 × 0.15 mm).

3D surface model construction

Bone contours were extracted with Insight Toolkit-Segmentation and Navigation Application (ITK-SNAP, version 3.8.0). The outer cortical margins of the distal femur and proximal tibia were traced slice by slice using a semi-automatic active-contour approach. The femur was segmented from the articular surface to 3 cm proximal to the distal femoral physis, and the tibia from the articular surface to 3 cm distal to the proximal tibial physis; the fibula and patella were excluded. Two musculoskeletal radiologists (with seven and eight years of experience), blinded to the clinical diagnosis, performed the segmentation together, and each contour was finalized only when both agreed. The final 3D bone surface models were exported in Neuroimaging Informatics Technology Initiative format and imported into 3D Slicer (version 5.0.3). Left knees were mirrored to right-sided orientation before landmarking.

Automated landmarking and statistical shape analysis

The workflow, adapted from previously validated protocols [21,23,24], consisted of template generation, automated propagation of corresponding landmarks, Procrustes superimposition with PCA, and statistical modeling. A template of 1003 pseudo-landmarks was distributed evenly over the external surface of a representative normal knee model (femur and tibia combined) using the pseudo-landmark generator in SlicerMorph [23]. The template was the control knee closest to the control-group mean shape.

Landmarks were propagated to every knee with the Automated Landmarking through Point-cloud Alignment and Correspondence Analysis (ALPACA) algorithm [24]. The template and each target surface were downsampled into point clouds and rigidly co-registered; the template point cloud was then non-rigidly warped to the target, and the template landmarks were transferred to the target surface by nearest-neighbor correspondence. ALPACA was run with its default settings. All landmark sets were visually checked for misplacement.

All configurations were superimposed by generalized Procrustes analysis (GPA), which removes differences in position, orientation, and scale. Because scaling removes overall size, the centroid size of each configuration was recorded and compared separately. Mean shapes of the DLM and normal groups were compared by the pointwise signed distance between them, mapped onto the mean normal surface; a positive value indicates that the DLM mean surface lies outside the normal mean surface along the surface normal, and a negative value indicates that it lies inside. The overall difference between group mean shapes was tested by a permutation test of the Procrustes distance between the group means (5000 permutations of group labels at the patient level, keeping both knees of a patient together). PCA was performed on the Procrustes coordinates of all 50 knees, and each principal component (PC) was interpreted by visualizing shapes at ±2.5 SD from the mean in SlicerMorph.

Separate bone models and knee pose

Because the femur and tibia were analyzed as one configuration, differences in knee flexion, rotation, and coronal alignment at the time of scanning could contribute to the shape components. We addressed this in two ways. First, the landmarks were partitioned into femoral (n = 546) and tibial (n = 457) sets by spectral clustering of a nearest-neighbor graph of the mean shape in which each edge was weighted by the stability of the distance between the two landmarks across knees (landmarks on the same bone keep nearly constant distances regardless of knee position); the assignment of every landmark was confirmed by its rigid co-movement with the femur or tibia, and GPA and PCA were repeated for each bone separately. This removes the relative position of the two bones from the shape analysis. Second, the tibiofemoral pose of each knee was estimated by superimposing its femoral landmarks on the mean femur and computing the rotation of its tibial landmarks relative to the mean tibia, expressed as flexion-extension, varus-valgus, and axial-rotation angles. For visualization of the femur-only results, the femoral surface of the control knee closest to the femoral mean shape was warped to each target landmark configuration with a thin-plate spline, and vertex displacements along the outward surface normal were color-mapped.

Statistical analysis

PC scores were standardized to a mean of 0 and SD of 1, and PCs 1-10 of each model were examined. Each PC was entered in a separate logistic regression model with DLM status as the dependent variable, first unadjusted and then adjusted for age and sex. To reduce small-sample bias and the risk of separation, we used Firth's penalized likelihood [25,26]. Because three DLM patients and one control contributed both knees, standard errors were estimated with a cluster-robust (sandwich) estimator with patients as clusters, and p-values were obtained from Wald tests. Results are presented as odds ratios (ORs) per 1-SD increase in PC score with 95% confidence intervals (CIs), and p-values were adjusted for the ten PCs of each model using the Holm method [27]. The sign of a PC is arbitrary; the femur-only PC4 was oriented so that higher scores indicate the DLM-like shape. As a sensitivity analysis, adjusted models were repeated with one knee per patient (16 DLM and 30 control knees), retaining the right knee of bilateral cases and, separately, the left knee.

Discrimination was estimated for a ridge-penalized logistic model (L2 penalty, $C = 1$) including PCs 1-10, age and sex, using 20 repeats of stratified five-fold cross-validation in which both knees of a patient were always assigned to the same fold. GPA and PCA were refitted on the training knees of each fold, and test knees were superimposed on the training mean shape and projected onto the training PCs. The cross-validated area under the receiver operating characteristic curve (AUC) is reported with a patient-level bootstrap 95% CI for the combined, femur-only, and tibia-only models.

Centroid size was compared with Welch's t-test and with linear regression adjusted for age and sex using patient-clustered standard errors. Pose angles were compared between groups with Welch's t-test and correlated with PC scores using Pearson's correlation. Landmarking and visualization were performed in SlicerMorph, and statistical analyses in Python (version 3.13.16) with NumPy (version 2.5.3), SciPy (version 1.18.1), and scikit-learn (version 1.9.1). Statistical significance was set at $p < 0.05$. Given the sample size, all analyses were considered exploratory.

Results

Mean shape differences and size

Figure 1 shows the mean surface models of the DLM and normal knees and the pointwise signed distance between them. Compared with normal knees, the lateral femoral condyle of DLM knees was smaller, particularly in its posterior and distal aspect (blue regions in Figure 1). Viewed from posteriorly, the lateral compartment joint space was subtly wider. The anterior part of the lateral femoral condyle and the lateral metaphysis lay outside the normal mean surface (yellow to orange regions), and the anterior part of the medial condyle showed a slight medial prominence; together these produced a wider femoral trochlear groove. On the tibia, the lateral slope of the lateral tibial spine lay lateral to the normal mean surface, indicating a more laterally positioned lateral tibial spine and a wider intercondylar eminence.

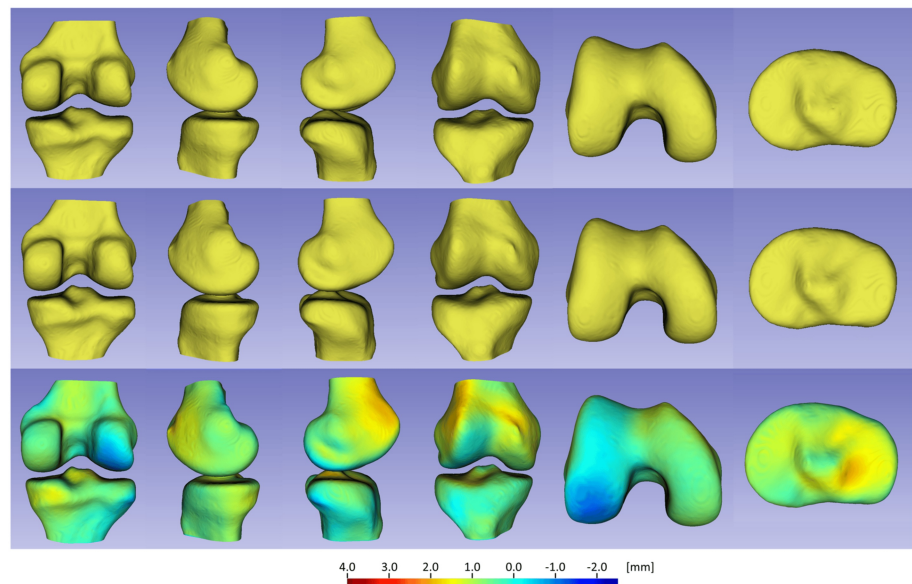


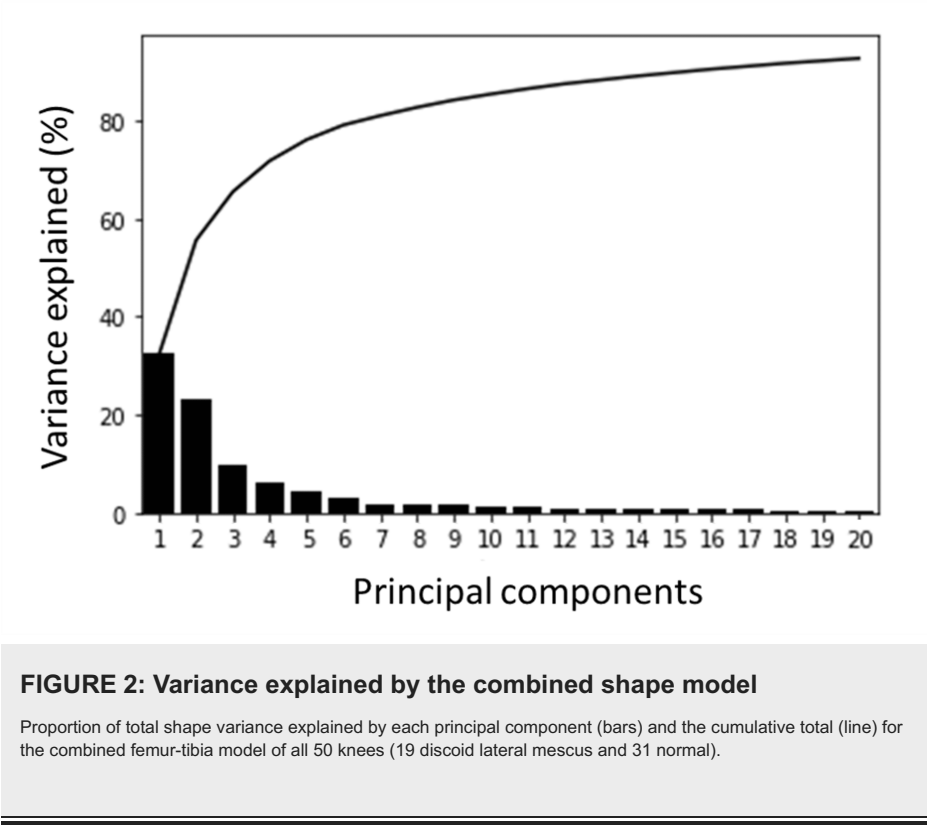
FIGURE 1: Mean shapes and regional differences

Mean surface reconstructions of the distal femur and proximal tibia in the discoid lateral meniscus (DLM) group (top) and the normal group (middle), with the pointwise signed-distance map between them (bottom). Positive values (yellow to red) indicate that the DLM mean surface lies outside the normal mean surface; negative values (blue) indicate that it lies inside. Panels show, from left to right, the posterior, medial, lateral, and anterior aspects of the femorotibial complex, the femoral inferior (articular) surface, and the tibial superior (plateau) surface.

Centroid size did not differ between groups (DLM 1181.2 ± 94.3 vs. normal 1197.1 ± 90.3 ; age- and sex-adjusted difference -16.2 , 95% CI -54.7 to 22.3 ; $p = 0.40$), nor did the centroid sizes of the femur ($p = 0.56$) or tibia ($p = 0.40$) alone. The difference between group mean shapes was of borderline significance for the combined configuration (permutation $p = 0.060$) and significant for the femur analyzed separately ($p = 0.037$) but not for the tibia ($p = 0.17$).

Principal components and knee pose

In the combined model, the first three PCs explained 65.5% of the total variance and the first ten 85.4% (Figure 2). PC1 (32.4%) captured knee position: the $+2.5$ SD shape represented a flexed knee with a smaller-appearing lateral femoral condyle, and the -2.5 SD shape an extended knee (Figure 3). PC1 scores were strongly correlated with the estimated tibiofemoral flexion angle ($|r| = 0.90$). PC2 (23.2%) mainly represented axial rotation of the tibia relative to the femur ($|r| = 0.97$ with the axial-rotation angle).



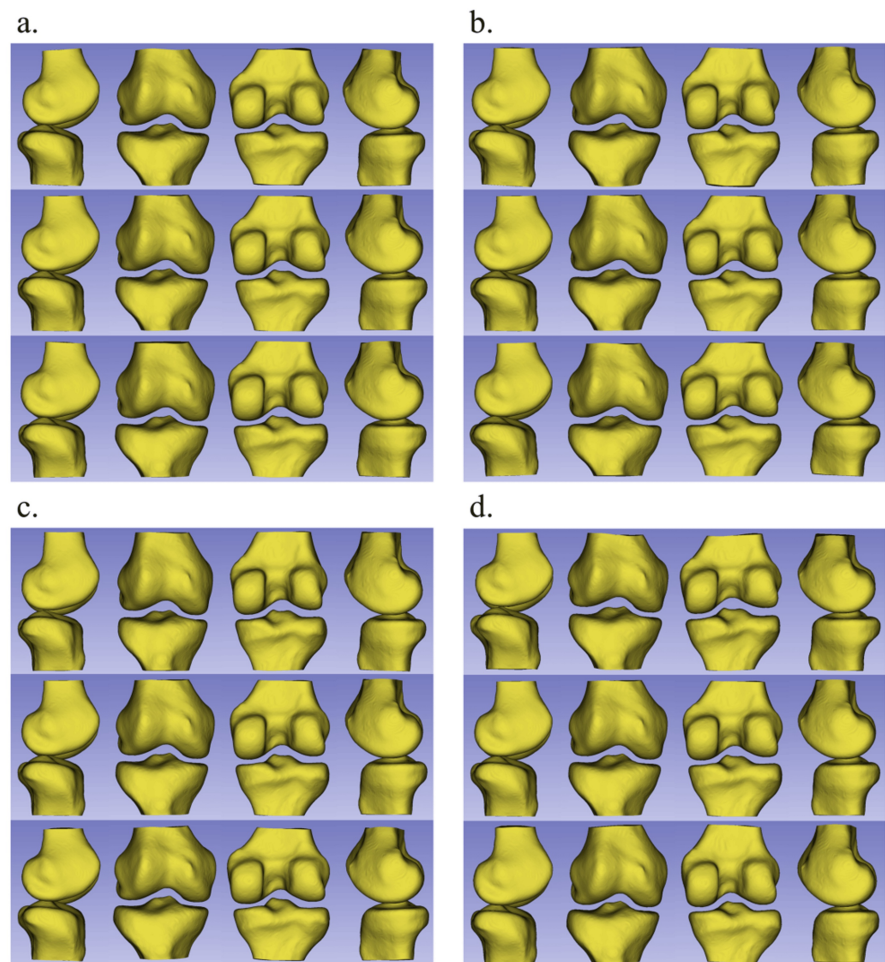


FIGURE 3: Principal components (PCs) of the combined model

Morphological extremes (mean $\pm$ 2.5 SD) of PC1 (a), PC3 (b), PC4 (c), and PC5 (d). Within each panel, medial, anterior, posterior, and lateral views are arranged from left to right, and rows show, from top to bottom, the +2.5 SD extreme, the mean configuration, and the -2.5 SD extreme.

PC3 (9.9%) and PC4 (6.3%) were related to intercondylar width. In PC3, the +2.5 SD shape showed a narrower femoral intercondylar region and longitudinal elongation, whereas the -2.5 SD shape showed a shorter longitudinal axis and a broader femoral intercondylar and trochlear width. PC4 mainly represented the width of the tibial intercondylar eminence, which was wider at the +2.5 SD extreme; changes on the femoral side were less distinct. In PC5, the +2.5 SD shape showed a wider intercondylar distance and a broader lateral compartment joint space, resembling a varus configuration, and the -2.5 SD shape a narrower lateral compartment joint space, resembling a valgus configuration. Neither PC4 nor PC5 was correlated with any pose angle ($|r| \leq 0.20$); the varus-valgus angle loaded mainly on PC6 ($|r| = 0.79$). Flexion ($p = 0.76$), varus-valgus ($p = 0.12$), and axial-rotation ($p = 0.44$) angles did not differ between groups.

Association of combined-model components with DLM

PC4 and PC5 of the combined model were associated with DLM in both unadjusted and age- and sex-adjusted models (adjusted OR per SD 3.31, 95% CI 1.15-9.53, $p = 0.027$; and 2.62, 95% CI 1.24-5.54, $p = 0.011$) (Table 1). Higher PC4 scores, representing a wider tibial intercondylar eminence, and higher PC5 scores, representing a wider intercondylar distance and a broader lateral compartment joint space, were associated with DLM. Neither association remained significant after Holm correction ($p = 0.24$ and 0.11). The positional components PC1 and PC2 were not associated with DLM. With one knee per patient, the adjusted ORs were 3.23 (1.24-8.40) and 3.14 (1.20-8.18) for PC4, and 3.76 (1.45-9.71) and 2.49 (1.13-5.51) for PC5, retaining the right and the left knee of bilateral cases, respectively.

PC	Unadjusted OR (95% CI)	p-value	Adjusted OR (95% CI)	p-value	Holm-adjusted p
PC1	1.62 (0.77–3.39)	0.202	1.68 (0.77–3.67)	0.194	1
PC2	0.93 (0.49–1.74)	0.811	0.93 (0.46–1.87)	0.835	1
PC3	0.56 (0.28–1.12)	0.103	0.51 (0.24–1.10)	0.085	0.678
PC4	2.18 (1.03–4.64)	0.042	3.31 (1.15–9.53)	0.027	0.24
PC5	2.68 (1.25–5.72)	0.011	2.62 (1.24–5.54)	0.011	0.113
PC6	1.12 (0.66–1.92)	0.672	1.12 (0.65–1.92)	0.688	1
PC7	1.05 (0.58–1.88)	0.876	1.05 (0.58–1.91)	0.876	1
PC8	0.72 (0.37–1.40)	0.331	0.72 (0.37–1.43)	0.353	1
PC9	1.52 (0.84–2.76)	0.164	1.54 (0.81–2.90)	0.185	1
PC10	0.98 (0.50–1.95)	0.962	0.98 (0.48–2.00)	0.96	1

TABLE 1: Association of principal components of the combined femur–tibia model with discoid lateral meniscus

Odds ratios (ORs) are per 1-standard deviation increase in the standardized PC score, from a separate Firth penalized logistic regression model for each PC with cluster-robust standard errors (patients as clusters; 50 knees, 46 patients). Adjusted models include age and sex. Holm-adjusted p-values refer to the adjusted models and account for the ten PCs tested.

CI - confidence interval; PC - principal component

Separate femoral and tibial models

In the femur-only model, PCs 1-10 explained 70.8% of the variance. PC4 (6.1%) was strongly associated with DLM (adjusted OR per SD 6.43, 95% CI 3.02-13.73; p < 0.001; Holm-adjusted p < 0.001), with consistent results with one knee per patient (5.48, 1.90-15.85, and 5.94, 1.95-18.08) (Table 2). Its DLM-like extreme showed inward displacement of the posterior and distal lateral femoral condyle, with outward displacement of the posterior medial condyle and the anterolateral condyle and metaphysis (Figure 4). This pattern closely matched the mean difference between groups (correlation between the two displacement maps, r = 0.81) and was partly shared by PC4 and PC5 of the combined model (|r| = 0.46 and 0.34 between scores). No other femoral component was associated with DLM. In the tibia-only model (PCs 1-10, 68.6% of variance), no component remained significant after Holm correction; PC5 was nominally associated (OR 0.36, 95% CI 0.17-0.78; p = 0.009; Holm-adjusted p = 0.089).

Model	PC	Variance (%)	Adjusted OR (95% CI)	p-value	Holm-adjusted p
Femur	PC1	26	0.59 (0.29–1.17)	0.131	1
Femur	PC2	12	0.98 (0.54–1.77)	0.948	1
Femur	PC3	7.6	1.50 (0.74–3.03)	0.262	1
Femur	PC4	6.1	6.43 (3.02–13.73)	<0.001	<0.001
Femur	PC5	4.8	0.83 (0.45–1.50)	0.534	1
Femur	PC6	3.9	1.03 (0.48–2.21)	0.932	1
Femur	PC7	3	1.34 (0.71–2.55)	0.368	1
Femur	PC8	2.7	1.32 (0.73–2.37)	0.362	1
Femur	PC9	2.5	1.08 (0.54–2.19)	0.824	1
Femur	PC10	2.3	1.35 (0.67–2.68)	0.4	1
Tibia	PC1	23.7	0.75 (0.41–1.40)	0.37	1
Tibia	PC2	9.1	0.81 (0.41–1.59)	0.544	1
Tibia	PC3	8.1	0.58 (0.28–1.20)	0.141	1
Tibia	PC4	5.5	0.88 (0.44–1.77)	0.72	1
Tibia	PC5	5.1	0.36 (0.17–0.78)	0.009	0.089
Tibia	PC6	4.3	1.36 (0.67–2.75)	0.397	1
Tibia	PC7	3.7	1.43 (0.76–2.66)	0.265	1
Tibia	PC8	3.5	1.17 (0.64–2.14)	0.603	1
Tibia	PC9	3	0.78 (0.46–1.34)	0.368	1
Tibia	PC10	2.6	0.93 (0.53–1.65)	0.814	1

TABLE 2: Age- and sex-adjusted association of principal components of the separate femur and tibia models with discoid lateral meniscus

Firth penalized logistic regression with patient-clustered standard errors; ORs per 1-standard deviation increase in PC score. PC signs are arbitrary; femur PC4 is oriented so that higher scores indicate the DLM-like shape.

CI - confidence interval; OR - odds ratio; PC - principal component

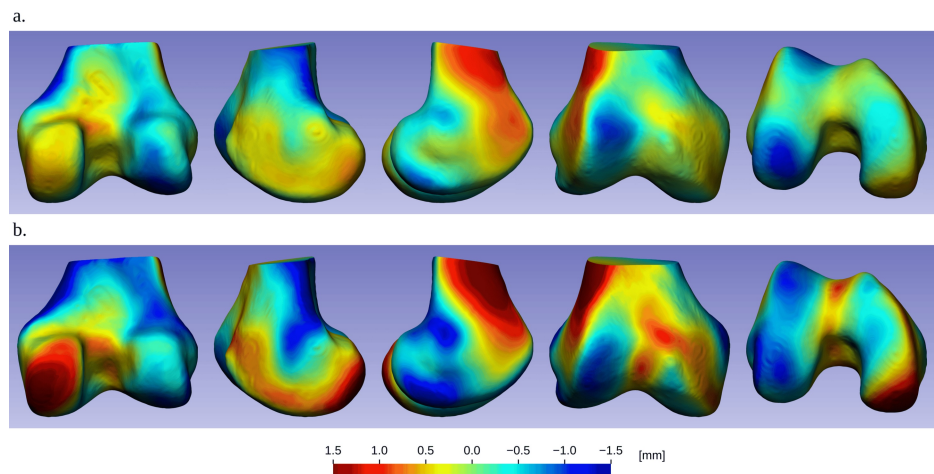


FIGURE 4: Femur-only principal component 4 (PC4)

(a) Signed displacement between the mean discoid lateral meniscus (DLM) and the mean control femur along the outward surface normal, shown on the control mean. (b) Displacement of the DLM-like extreme (+2.5 SD) of femur PC4 relative to the mean shape. Both maps are shown on the femur of the control knee closest to the mean shape, warped to each configuration with a thin-plate spline. Red, outward; blue, inward (mm). Views from left to right: posterior, medial, lateral, anterior, and distal (articular). The two maps are closely correlated ($r = 0.81$).

Discrimination

Cross-validated AUCs were 0.78 (95% CI 0.65-0.90) for the combined model, 0.80 (0.64-0.92) for the femur-only model, and 0.63 (0.46-0.80) for the tibia-only model.

Discussion

This study used 3D MRI-based SSA to characterize bone shape in knees with DLM. The DLM femur showed a posterior and distal deficit of the lateral femoral condyle with relative prominence of the anterolateral condyle and metaphysis. In a femur-only shape model, this pattern was captured by a single component that was strongly associated with DLM independently of age and sex and remained significant after correction for multiple testing. In the combined femur-tibia model, components representing intercondylar width and lateral compartment joint space were associated with DLM before, but not after, correction for multiple testing, whereas the largest components reflected knee position at the time of scanning.

To our knowledge, this is the first study to use 3D MRI-based SSA to compare bone morphology between knees with and without DLM. Previous studies relied on radiographic signs and selected measurements [8-12,14], which are limited by two-dimensional assessment and inter-reader variability. The present approach analyzes the whole bone surface without predefined measurements and shows how the individual findings relate to one another.

The smaller lateral femoral condyle, most marked posteriorly, is consistent with previously reported radiographic signs, such as squaring of the lateral femoral condyle, in which the lowest point of the lateral femoral condyle extends further laterally in DLM [28]. A reduced volume of the posterior lateral femoral bone has been demonstrated with posterior lateral and medial condylar angles on knee MRI [4], and the lowest point of the lateral femoral condyle has been found to be more lateral in DLM knees, indicating hypoplasia of the lateral femoral condyle [13]. Within DLM knees, a narrower lateral femoral condyle has also been associated with meniscal tears [17]. Our analysis visualizes this hypoplasia in 3D and shows that it is regional: the deficit is concentrated posteriorly and distally, whereas the anterior lateral condyle and metaphysis are relatively prominent. This combination is better described as an altered profile of the lateral condyle than as uniform hypoplasia. The same pattern was captured by a single femur-only component, which is independent of tibial position, and overall size did not differ between groups, so the pattern is unlikely to be an artifact of knee positioning or body size. Together with a slight medial prominence of the anterior medial condyle, these changes produced a wider femoral trochlear groove. We also observed subtle widening of the lateral compartment joint space, consistent with conventional radiographic findings [12,28].

On the tibia, the lateral slope of the lateral tibial spine was displaced laterally, widening the intercondylar eminence. Because the signed distance is measured along the surface normal, this indicates lateral displacement of the spine rather than an increase in its height. This is consistent with MRI evidence of a lower lateral tibial spine together with a wider tibial eminence in complete DLM [15] and with radiographic widening of the eminence [14]. Tibial differences were, however, less consistent than femoral ones: the tibial

mean shapes did not differ significantly between groups (permutation $p = 0.17$), no tibial component remained significant after correction for multiple testing, and the tibia-only model discriminated poorly (cross-validated AUC 0.63). This is in line with a recent pediatric MRI study in which tibial eminence width and lateral tibial spine height did not differ between knees with and without DLM [16].

The first PCs of a shape model often capture size and position rather than disease [29]. In the combined model, PC1 and PC2 mainly represented knee flexion and tibial axial rotation at the time of scanning and were not associated with DLM. Such positional variation is inherent in analyzing two articulating bones as one configuration, and the separate bone models avoid it. PC4 of the combined model mainly represented the width of the tibial intercondylar eminence, and its DLM-associated extreme had a wider eminence, consistent with the mean-shape comparison and with previous studies [14,15]. PC5, linked to the intercondylar distance and lateral compartment joint space, resembled varus or valgus configurations, but it was not correlated with the estimated varus-valgus angle, suggesting that it reflects bone shape rather than coronal alignment during scanning; its association with DLM is consistent with radiographic lateral joint space widening [12,28]. Because these combined-model associations did not survive correction for multiple testing, they should be regarded as hypothesis-generating.

The bony morphology of DLM knees could arise from at least two mechanisms that our cross-sectional data cannot distinguish. First, it may be adaptive. During childhood, the epiphyses undergo endochondral ossification, and a thick DLM may act as an abnormally large cushion that alters load distribution across the lateral compartment [30]. Such a load-sparing effect could reduce bone growth, particularly in the posterolateral femoral condyle, where loading stress is thought to be concentrated, and alter tibial plateau morphology [4,13,30]. Second, the bony features may represent a primary developmental variant that coexists with, or predisposes to, the discoid meniscus. Longitudinal imaging of children with DLM, including before and after saucerization, would be needed to separate these explanations.

The strengths of this study include whole-surface 3D analysis beyond conventional linear or angular measurements; the use of open-source software (SlicerMorph and ALPACA), which supports reproducibility; separate bone models and pose estimation to distinguish shape from position; and penalized regression with patient-level clustering and cross-validation, which reduces, but does not remove, the risk of overfitting in a small sample.

This study has several limitations. First, the sample was small (19 DLM knees), the analysis was exploratory, the models were not validated in an external cohort, and their calibration could not be assessed reliably; shape components and their associations may therefore be unstable. Second, three DLM patients and one control contributed both knees; we accounted for this with clustered standard errors and a one-knee-per-patient sensitivity analysis, but residual dependence cannot be excluded. Third, knees were scanned in a non-standardized position; although pose did not differ between groups and the main femoral finding was confirmed in a femur-only model, positional variation reduces the sensitivity of the combined model. Fourth, the DLM group included complete and incomplete types and knees with and without tears, and only 10 of 19 DLM knees had arthroscopic confirmation; a subtle incomplete DLM in a control knee cannot be fully excluded without arthroscopy. Fifth, height, body mass index, limb alignment, and skeletal maturity were not fully controlled, although centroid size did not differ between groups. Sixth, all participants were Japanese and younger than 30 years; because DLM prevalence and knee morphology differ between populations, the findings may not generalize to other ethnic groups or older patients. Seventh, segmentation was performed by consensus of two observers, so interobserver reproducibility could not be quantified; small contour differences may add noise to the shape models, although they would be expected to weaken rather than create group differences. Finally, the analysis focused on bone, and the shape of the articular cartilage was not analyzed. Future studies should include larger and more diverse cohorts, incorporate cartilage morphology, evaluate diagnostic performance prospectively, and examine the functional implications of these shape variations through biomechanical modeling or longitudinal studies.

Conclusions

In this exploratory study, 3D MRI-based SSA showed that knees with symptomatic DLM have a distinct pattern of bony morphology. The most consistent feature was posterolateral hypoplasia of the lateral femoral condyle with relative anterolateral prominence, which was associated with DLM independently of age, sex, knee position, and overall size. Shape components representing a wider tibial intercondylar eminence and lateral compartment joint space were also associated with DLM, although not after correction for multiple testing. These hypothesis-generating findings require validation in larger, more diverse cohorts, and longitudinal studies are needed to determine whether the morphology is predisposing or adaptive and whether it has diagnostic value.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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Disclosures

Human subjects: Informed consent for treatment and open access publication was obtained or waived by all participants in this study. The Research Ethics Committee of Saitama Medical University Hospital issued approval 2023-046. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

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