



DEEP lateral femoral notch sign is associated with lateral meniscus tear and non-spherical lateral femoral condyle in ACL deficient knee

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Abstract

Purpose This study investigates the relationship between the deep lateral femoral notch sign, lateral meniscus injury, and knee morphology in patients with ACL injuries.

Methods We retrospectively analyzed MRI scans of 74 knees from 73 patients who underwent primary ACL reconstruction. These knees were selected from an initial cohort of 173 knees from 170 patients. We measured the Lateral Femoral Condyle Index, Lateral Femoral Condyle Ratio, Lateral Femoral Condyle Height/Depth Ratio (LFCR H/D), assessed LNS both qualitatively and quantitatively, and evaluated tibial slope and the presence of lateral meniscus injury. We then compared groups based on the following criteria: tibial slope > 12°, LFCI < 0.7 (indicating non-spherical femurs), LNS > 2 mm, presence of lateral meniscus injury, increased average/median LFCR, and decreased average/median LFCR H/D.

Results We found a significant association between LNS > 2 mm and lateral meniscus injury ($p = 0.04$). This association was also present when comparing knees with LNS > 2 mm to those with absent LNS ($p = 0.03$). Additionally, LNS > 2 mm was associated with LFCI < 0.7 ($p = 0.03$) when comparing subgroups with LNS > 2 mm and absent LNS. Decreased median LFCR H/D values were associated with decreased LFCI values ($p = 0.04$). Finally, knees with both LNS > 2 mm and lateral meniscus injury showed decreased median LFCR H/D values ($p = 0.04$).

Conclusions In conclusion, our findings indicate that LNS > 2 mm is associated with lateral meniscal injury and LFCI < 0.7. Furthermore, knees exhibiting both lateral meniscus lesions and LNS > 2 mm demonstrate decreased median values of LFCR H/D.

Keywords Anterior cruciate ligament · Knee · Magnetic resonance imaging · Lateral femoral notch sign · Rotational instability

Introduction

The morphology of the tibia (increased tibial slope) and femur (deep lateral femoral condyle or altered condylar sphericity) influences joint stability and can predict

increased laxity, although the precise mechanisms remain unclear [1]. In the femur, a lateral femoral notch sign (LNS) depth exceeding one millimeter is highly predictive of anterior cruciate ligament (ACL) injury [2]. Depths greater than 2 millimeters correlate with increased rotational laxity [3] or

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lateral meniscus injury [4, 5], particularly affecting its posterior root [6]. Alterations in lateral femoral condylar sphericity may exacerbate rotational instability due to changes in the knee's flexion radius throughout its range of motion [7]. A decreased lateral femoral condylar index (LFCI < 0.7) indicates a reduced posterior flexion radius, altered sphericity, and modified femoral rolling over the tibia. This is associated with increased sliding of the flattened anterior condyle over the convex lateral tibial plateau, leading to a more pronounced pivoting mechanism and a higher risk of primary ACL ruptures or re-ruptures [7]. Another explanation for the association between decreased LFCI and ACL ruptures or re-ruptures is the increased tension on the native ACL or graft due to altered bone morphology and suboptimal positioning [7]. Patients with increased posterior depth of the lateral femoral condyle and ACL injury exhibit greater knee rotational instability [8–12]. An increased lateral femoral condylar ratio (LFCR) and a decreased lateral femoral condylar height/depth ratio (LFCR H/D) are indicative of a more oval-shaped lateral femoral condyle with an increased diameter. This morphology can alter knee mechanics by modifying the femoral excursion radius during flexion–extension, reducing tension in lateral stabilizing structures at low flexion angles and compromising the secondary stabilizers of the ACL [12]. Despite all this data, femoral morphological alterations are still not understood as indications for lateral extra-articular procedures in the ACL reconstructed knee [13].

A knee with a steep tibial slope, increased anterior tibial subluxation, significant lateral femoral condyle depth, and meniscal deficiency represents a challenging scenario for ACL reconstruction and is commonly observed in patients with ACL tears [9]. Patients with a decreased LFCI and increased lateral tibial slope face a heightened risk of ACL tear or re-tear [7].

This study aims to investigate signs of increased rotational laxity (concomitant lateral meniscus tear or lateral femoral notch sign) in an ACL-injured population, correlating these signs with morphological parameters (LFCI, LFCR, LFCR H/D, and tibial slope). We hypothesize that a deep LNS and lateral meniscus injury are interlinked and associated with specific femoral and tibial morphological features.

Methods

Subjects

This observational, cross-sectional study was approved by a Research Ethics Committee (Protocol #36,294,820.9.0000.5273) and conducted in accordance with the Declaration of Helsinki. The sample comprised

participants who underwent ACL reconstruction between 2012 and 2021 at the knee surgery center of a private hospital. Participants were selected based on the availability of preoperative magnetic resonance imaging of the knee and were aged between 15 and 60 years, of both sexes. Exclusion criteria included joint infection, axis deviation requiring osteotomy, ACL revision surgery, fracture at the knee level, patellar instability, or concomitant posterior cruciate ligament injury or collateral ligament injury.

Image acquisition was performed preoperatively using a 1.5 Tesla MRI device (Intera Philips®—Amsterdam, Netherlands). A standardized technique was employed with patients in the supine position, acquiring sequential images in 3 planes (sagittal, coronal, and axial) with a minimum interslice spacing of three millimeters.

Measurements of lateral femoral notch sign depth, tibial slope, lateral femoral condylar ratio, lateral femoral condylar height/depth ratio (LFCR H/D), and lateral femoral condylar index, as well as the date of the examination and the presence of ligament, meniscal, and osteochondral injuries, were performed by a single orthopedic surgeon specialized in knee surgery with PhD in Radiology and experienced with the measurement of the evaluated parameters. Electronic software (Philips IntelliSpace PACS—Philips®—Amsterdam, Netherlands) was used for analysis of T1-weighted sagittal images, with simultaneous reference to axial and coronal planes, according to established guidelines [3, 7, 9, 12, 14] for each parameter.

Morphology assessment

Tibial slope

Was measured on T1-weighted sagittal MRI images. First, the anatomical axis of the tibia was determined. A point placed at the center of the lateral tibial plateau in the axial plane was used to correlate with the sagittal plane. Next, the anatomical axis was copied onto the sagittal image. The tibial slope was then measured as the angle formed between a line perpendicular to the long axis of the tibial diaphysis and a line tangent to the most superior points of the anterior and posterior aspects of the lateral tibial plateau. (Fig. 1) [14].

Lateral femoral notch sign (LNS)

The presence of the LNS was assessed on T1-weighted sagittal MRI images. The depth of the LNS was measured in millimeters. A straight line was drawn between the most anterior and posterior edges of the osteochondral lesion. A perpendicular line was then drawn from this line to the deepest point of the notch, and the length of this perpendicular line represented the depth of the LNS. (Fig. 2) [3, 5, 6, 9].



Fig. 1 Tibial slope measurement. After previous correspondence in the axial plane of the central plane of the lateral tibial plateau, an image is visualized in the sagittal plane of the T1 weighting, angle between the long axis of the diaphysis and the joint surface

Lateral femoral condylar index (LFCI)

The sphericity of the lateral femoral condyle was assessed on T1-weighted sagittal MRI images. The mid-sagittal plane of the lateral femoral condyle was identified as the T1 sagittal image where the popliteal tendon groove was most prominent on the corresponding coronal T1 image. On this plane, flexion and extension curvatures were estimated by determining the corresponding circles. The extension circle

(B) was determined by the sphericity that best fit the curvature of the anterior subchondral bone, passing through the distal (6 o'clock) and anterior (9 o'clock) points. Similarly, the flexion circle (A) was determined by the sphericity that best fit the curvature of the posterior subchondral bone, passing through the distal (6 o'clock) and posterior (3 o'clock) points. [7]. The LFCI was then calculated to quantify this sphericity by dividing the diameter of the flexion circle (A) by the diameter of the extension circle (B): $LFCI = A/B$. A lower LFCI indicates a less spherical condyle, potentially contributing to the rotational instability that can predispose to ACL injury. (Fig. 3).

Lateral femoral condylar ratio (LFCR) and lateral femoral condylar height/depth ratio (LFCR H/D)

2 methods were used to assess posterior femoral condylar depth. The LFCR was originally evaluated on lateral knee radiographs using the intersection of the femoral shaft axis and the femoral condylar axis. The LFCR is the distance between this intersection point and the most posterior point of the lateral femoral condyle, divided by the total lateral condylar axis (Fig. 5). To standardize the study, a modified method was used on T1 MRI images, respecting the same anatomical parameters. Sagittal plane images displaying the largest anteroposterior lateral condylar diameter projected onto the long axis of the femoral diaphysis were used, similar to the radiographic evaluation [8]. Lateral condylar depth was also assessed by measuring the LFCR H/D using MRI [9]. After identifying the most posterior subchondral portion of the lateral femoral condyle in the axial plane images,

Fig. 2 Measurement of the depth of the lateral femoral notch sign on an MRI image in the sagittal plane of T1 weighting. The LNS corresponds, in millimeters, to the distance between the greatest depth of the depression and the line tangent to the anterior and posterior edges of the lesion. On the right enlarged image showing the measurement performed. MRI: magnetic resonance imaging; LNS: lateral femoral notch sign

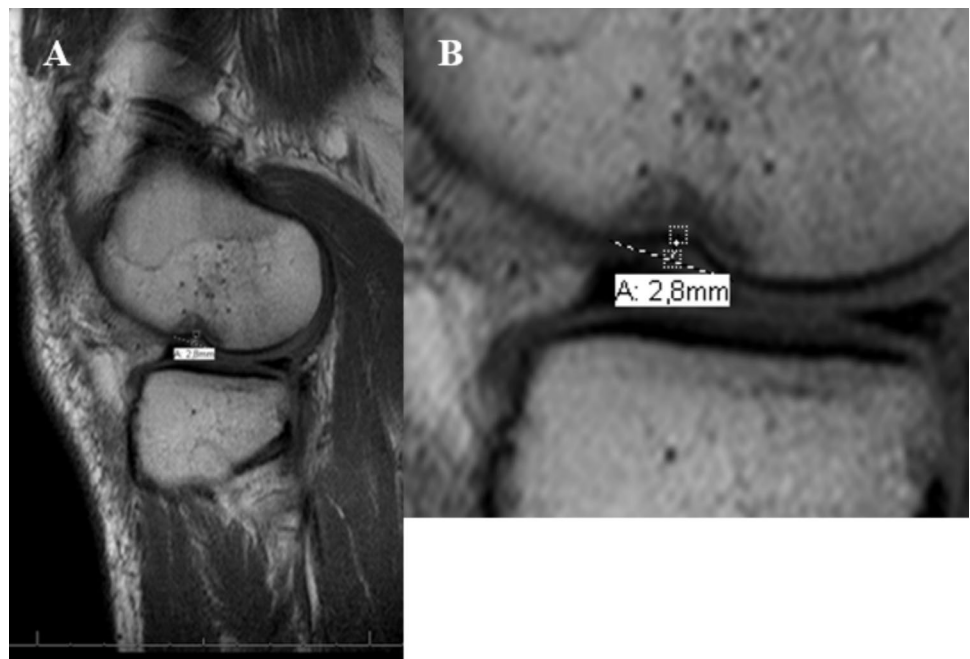




Fig. 3 Measurement of the lateral femoral condylar index (LFCI) on a sagittal T1 MRI image. Using a T1-weighted MRI image in the sagittal plane, the diameters of the extension (anterior, B) and flexion (posterior, A) circles are measured to determine the LFCI. LFCI: lateral femoral condylar index; MRI: magnetic resonance imaging



Fig. 4 Measurement of lateral femoral condylar ratio (LFCR) in sagittal T1 MRI image. The long femoral shaft (A, vertical line) was determined by a line through the center of the femoral shaft. The axis of the femoral condyle (B, horizontal line) was determined by a line between the most posterior and anterior points of the lateral condyle. The distance from the intersection of these lines to the posterior end of the condyle was divided by the total anteroposterior length of the condyle. LFCR: lateral femoral condylar index; MRI: magnetic resonance imaging

this plane was projected onto the sagittal T1 (Fig. 4). The femoral axis was identified, and a line tangent to the condyle and parallel to the femoral axis was drawn (line A).

The perpendicular line connecting line A with the femoral axis was defined as the lateral femoral condylar depth (line C). A line tangential to the most distal portion of the lateral femoral condyle and perpendicular to the femoral axis was drawn (line B). The distance between lines C and B was measured as the lateral femoral condylar height. The ratio between height and depth was then calculated to obtain the LFCR H/D value (Fig. 5). Values approaching one indicate a more spherical shape, while values approaching zero indicate a more elliptical shape with a deeper lateral femoral condyle. [9].

Cut-off Values for Parameter Analysis: Based on the literature, cut-off values associated with a higher incidence of rotational instability or re-injury were used to separate and compare the groups. These values were: tibial slope > 12 degrees, LFCI < 0.7, and LNS > 2 mm (the LNS > 2 mm group was also compared to the LNS absent group). LFCR and LFCR H/D were analyzed according to mean values and their distribution, as fixed abnormality values have not been established.

Statistical analysis

The normality of continuous quantitative variables was assessed using the Shapiro–Wilk test, which is suitable for small sample sizes to determine if data follows a normal distribution. Quantitative variables are presented using measures of central tendency (mean and median) and variability (standard deviation, 25th percentile, and 75th percentile). Normally distributed variables were compared using one-way analysis of variance, which assesses differences in means between multiple groups. Non-normally distributed variables were compared using the Kruskal–Wallis test, a non-parametric alternative to ANOVA when data is not normally distributed. For pairwise median comparisons, the Mann–Whitney U test was used, a non-parametric test to compare two independent groups. Categorical variables are presented as absolute and relative frequencies (percentages) and compared using the chi-square test (χ^2) to assess associations between categorical variables, or Fisher's exact test when sample sizes were small or expected cell counts were low, providing a more accurate *p*-value. To measure the magnitude of association between selected categorical variables, unconditional logistic regression was performed, modeling the probability of a binary outcome, and odds ratios with 95% confidence intervals were calculated. A significance level of $p \leq 0.05$ was used for all statistical tests. Statistical analyses were performed using IBM SPSS Statistics 21.0.

Sample Size Justification: Assuming an ACL tear rate between 60 and 70 per 100,000 person-years [15], a sample size of 72 participants was determined to achieve a sampling

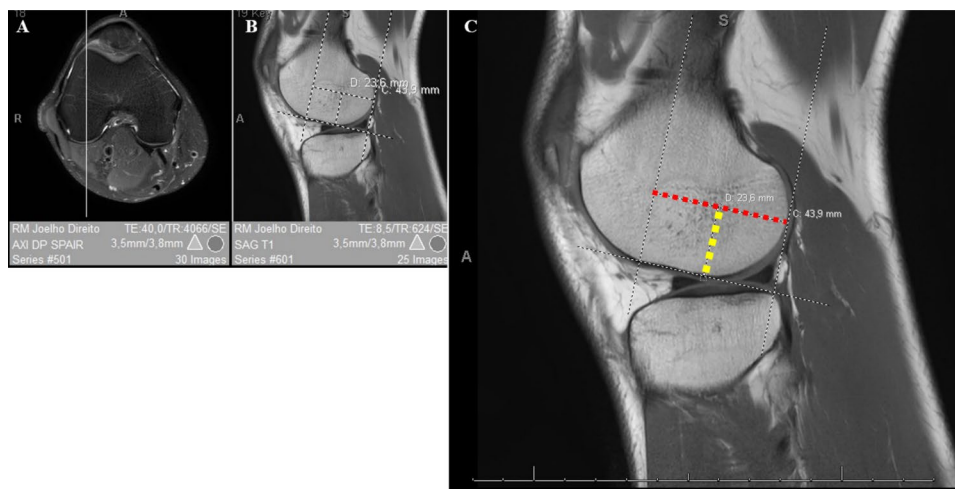


Fig. 5 Measurement of the lateral femoral condylar height/depth ratio (LFCR H/D) using MRI image in the T1 sagittal plane. **A** Initially, the T2 axial plane of the MRI image, in which the lateral femoral condyle has greater depth, is used as a reference. **B** Next, the corresponding image in the sagittal plane of the T1 weighting is used to perform the measurement of the studied ratio. **C** The femoral anatomical axis is traced (dashed vertical line). Then, a line parallel to this axis is drawn, tangent to the posterior edge of the lateral femoral condyle. The distance between the 2 lines, at the highest depth of

the condyle, corresponds to the studied depth (dotted red line). A last parallel line is drawn distally tangent to the distal limit of the lateral femoral condyle. The distance between the depth lines (dotted red line) and the distal line tangent to the lateral femoral condyle in its most distal portion corresponds to the evaluated height (dotted yellow line). LFCR H/D is defined by the ratio between condylar height (dotted yellow line) and condylar depth (red dotted line). LFCR H/D: lateral femoral condylar height/depth ratio; MRI: magnetic resonance imaging

error of 2%, a confidence level of 95%, and a statistical power of 80%.

Results

A total of 173 knees from 170 patients with ACL injuries who underwent ACL reconstruction at our institution were initially identified. After excluding 99 knees (4 multiligament reconstructions, 1 ACL revision, and 94 without MRI at our hospital), 74 knees from 73 patients were included in the final analysis. The cohort consisted of 13 females (17.8%) and 60 males (82.2%), with a mean age between 21 and 30 years (46.6% of the sample). ACL-R was performed using hamstring autografts in 39 patients and bone-tendon-bone autografts from the patellar tendon in 35 patients. Frequencies of the studied variables and mean values are presented in Tables 1 and 2, respectively.

Key findings

- Patients with lateral meniscal injuries were significantly more likely to have a deep lateral femoral notch sign (LNS > 2 mm) compared to those without meniscal injury (20% vs. 6.1%, $p = 0.04$) (Table 2). Similarly, a significantly higher proportion of patients with lateral

meniscal injuries had a deep LNS compared to those with an absent LNS (33.3% vs. 9.4%, $p = 0.03$) (Table 2).

- While there was no significant association between $LNS \leq 2$ mm and $LNS > 2$ mm (Table 3A), a significantly greater proportion of patients with $LNS > 2$ mm had a low lateral femoral condylar index (LFCI < 0.7) compared to those with an absent LNS (37.5% vs. 7.7%, $p = 0.03$) (Table 3B).
- Lower median lateral femoral condylar ratio height/depth (LFCR H/D) was significantly associated with $LFCI < 0.7$ ($p = 0.04$) (Table 4).
- Patients with both $LNS > 2$ mm and lateral meniscus injury had significantly lower median LFCR H/D values compared to all other patients ($p = 0.04$) (Table 5).
- No significant associations were found between any of the studied parameters and tibial slope (greater than or equal to 12 degrees vs. less than 12 degrees).

Discussion

Our study revealed a significant association between a deep lateral femoral notch sign ($LNS > 2$ mm) and lateral meniscus injury ($p = 0.04$). This finding supports our initial hypothesis that deep LNS and lateral meniscus injury are linked. Prior research using radiographs and MRI images in 84 patients with ACL tears [5], and another study with simple lateral radiographs and sagittal MRI images of 500

Table 1 Femorotibial variables in the study population expressed by frequency (A) and mean (B)

A	
Evaluated variables	n = 74 knees (%)
LNS	
≤ 2 mm	66 (89.2)
> 2 mm	08 (10.8)
Lateral meniscus	
No injury	49 (66,3)
With injury	25 (33,7)
Tibial slope	
≤ 12 degrees	61 (82,5)
> 12 degrees	13 (17,5)
LFCI	
≤ 0,7	60 (81,1)
> 0,7	14 (18,9)
B	
Evaluated variables	n = 74 knees
Tibial slope	
Average (SD)	9,38 (2,85)
Median (P ₂₅ –P ₇₅)	9,0 (8,0–11,0)
LFCI	
Average (SD)	0,76 (0,07)
Median (P ₂₅ –P ₇₅)	0,75 (0,72–0,82)
LFCR	
Average (SD)	0,61 (0,04)
Median (P ₂₅ –P ₇₅)	0,61 (0,59–0,64)
LFCR H/D	
Average (SD)	0,49 (0,04)
Median (P ₂₅ –P ₇₅)	0,49 (0,46–0,51)

patients with arthroscopically confirmed acute ACL injuries, also concluded that an LNS > 2 mm correlates with lateral meniscal tears [4]. Another study, similar to ours in its use of MRI, evaluated 115 patients with ACL injuries and demonstrated that the presence of LNS on preoperative MRI can be predictive of injury to the posterior root of the lateral meniscus [16]. These findings reinforce the concept that LNS > 2 mm may indicate increased rotational laxity or lateral meniscus injury, particularly in its posterior root.

Lateral meniscus injury, especially of the posterior root, or surgical treatment with meniscectomy may lead to residual instability even after ACL reconstruction [9, 17, 18]. ACL injuries associated with lateral meniscus injury have a high rate of high-grade rotational instability. The association between lateral meniscal injury and increased LNS depth [4–6] suggests that both factors are related to increased knee rotational instability. There is logical sense in the association between deeper LNS and lateral meniscal injury since both are involved with increased rotational instability in the knee with ACL injury. It remains uncertain

whether a cause-and-effect relationship exists between them, if they occur simultaneously in a single episode, or if they result from cumulative instability episodes. The association between the LNS and lateral meniscus tears may be due to the increased tension of the native ACL or the reconstructed ligament, due to the altered bone morphology and consequent poor positioning of the native or grafted ligament.

We identified that a deep LNS (LNS > 2 mm), compared to the absence of LNS, was associated with a lower lateral femoral condylar index (LFCI < 0.7) ($p = 0.03$). LNS > 2 mm is a known preoperative predictor of high-grade rotational instability in knees with ACL injuries, as demonstrated by quantitative intraoperative pivot shift kinematic evaluation in 90 patients undergoing ACL reconstruction [3]. Thus, our finding suggests that a femur with altered sphericity, as indicated by a lower LFCI, is associated with a well-established criterion of increased rotational instability (LNS > 2 mm). This leads us to propose that LFCI < 0.7 could also be considered a predictor of high-grade rotational instability. Interestingly, we did not find the same association when

Table 2 Comparison of variables between groups with and without injury to the lateral meniscus

Evaluated variables	No LM injury n = 49 (%)	With LM injury n = 25 (%)	p value
LNS			
≤ 2 mm	46 (93.9)	20 (80.0)	0.04
> 2 mm	3 (6.1)	5 (20.0)	
LNS			
Absent	29 (90.6)	10 (66.7)	0.03
> 2 mm	3 (9.4)	5 (33.3)	
Tibial slope			
≤ 12 degrees	39 (79.6)	22 (88.0)	0.52
> 12 degrees	10 (20.4)	3 (12.0)	
LFCI			
≥ 0.7	40 (81.6)	20 (80.0)	0.89
< 0.7	9 (18.4)	5 (20.0)	
LFCR			
Average (SD)	0.61 (0.04)	0.62 (0.04)	0.52
Median (P ₂₅ –P ₇₅)	0.61 (0.59–0.64)	0.62 (0.60–0.64)	0.72
LFCR H/D			
Average (SD)	0.49 (0.04)	0.49 (0.05)	0.89
Median (P ₂₅ –P ₇₅)	0.49 (0.46–0.51)	0.49 (0.46–0.51)	1.00

Chi-square test: comparison between percentages (LNS, LFCI, tibial slope)

Mann Whitney test: mean/median comparison (LFCR, LFCR H/D)

comparing the LNS ≤ 2 mm and LNS > 2 mm groups. This might be due to our sample size or the possibility that altered femoral shape is primarily associated with greater instability (LNS > 2 mm) and not with smaller LNS lesions. Our findings support the idea that a decreased lateral femoral condylar index indicates a decreased flexion radius, change in sphericity and femur rolling over the tibia, associated with greater sliding of the flattened anterior part of the condyle over the convex lateral tibial plateau, with a more exuberant pivoting mechanism.

The lateral femoral condylar ratio and lateral femoral condylar ratio height/depth (LFCR H/D) both assess the depth of the lateral femoral condyle, but use different methods and have opposite numerical relationships; both have been associated with greater rotational instability [12]. Increased LFCR is an independent risk factors for meniscal injuries [19], and also associated with ramping lesions in the posterior horn of the medial meniscus [10], lateral meniscus posterior root tears in patients with acute ACL injuries [20] and a higher risk of ACL injury with a non-contact trauma mechanism in an Asian population [11, 21]. Interestingly, there is a lack of studies directly correlating these two evaluation methods; typically, only one is used in research [8–12]. Given the absence of a fixed cut-off value in the literature, we evaluated both LFCR and LFCR H/D in terms of their means and medians, rather than separating them into defined groups. Even so, the LFCR H/D showed relevant associations in our analysis. The relationship between decreased LFCR H/D and increased instability was reported in a study

[9] evaluating three patient groups: primary lesion, single ACL reconstruction failure, and multiple failures. In practical terms, a lateral femoral condyle with greater depth in relation to its height could be associated with recurrence of ACL failure [9]. This makes sense because patients with increased posterior depth of the lateral femoral condyle and ACL injury have greater knee rotational instability.

We also found a significant association ($p = 0.04$) between two evaluation parameters of femoral morphology: decreased LFCI (non-spherical femoral condyle) and decreased median LFCR H/D (deep lateral femoral condyle). This suggests a potential pattern of morphological change, indicated by the presence of one or both of these factors. Mechanically, the detrimental effect of a deeper lateral femoral condyle (as translated by increased LFCR or decreased LFCR H/D) can be explained by an altered tibiofemoral interaction. The clinical consequence of this increased instability has been studied, demonstrating that increased LFCR is a risk factor for ramp injury in the red zone of the medial meniscus [10] and ACL injury [11]. Decreased LFCI has been reported to be associated with ACL rupture or ACL graft rupture [6], but not found to be a risk factor for noncontact ACL injury [22].

Finally, we found a significant association corresponding to a decreased median value of LFCR H/D in the group with lateral meniscal injury combined with LNS > 2 mm. This can be interpreted as an association of a femur with greater depth (an altered anatomy) with two factors associated with increased rotational instability. The cumulative

Table 3 Comparison of variables between groups stratified by LNS depth

A			
Evaluated variables	LNS ≤ 2 n=66 (%)	LNS > 2 n=08 (%)	p value
Tibial slope			
≤ 12 graus	57 (86.4)	7 (87.5)	0.92
> 12 graus	9 (13.6)	1 (12.5)	
LFCI			
$\geq 0,7$	55 (83.3)	5 (62.5)	0.09
$< 0,7$	11 (16.7)	3 (37.5)	
LFCR			
Average (SD)	0.61 (0.39)	0.60 (0.41)	0.64
Median (P ₂₅ –P ₇₅)	0.61 (0.60–0.64)	0.60 (0.57–0.63)	0.76
LFCR H/D			
Average (SD)	0.49 (0.04)	0.47 (0.05)	0.47
Median (P ₂₅ –P ₇₅)	0.49 (0.47–0.51)	0.48 (0.43–0.52)	0.35
B			
Evaluated variables	LNS absent n=39 (%)	LNS > 2 n=08 (%)	p value
Tibial slope			
≤ 12 graus	34 (87.2)	7 (87.5)	0.94
> 12 graus	5 (12.8)	1 (12.5)	
LFCI			
$\geq 0,7$	36 (92.3)	5 (62.5)	0.03
$< 0,7$	3 (7.7)	3 (37.5)	
LFCR			
Average (SD)	0.61 0.61 (0.05)	0.60 (0.41)	0.59
Median (P ₂₅ –P ₇₅)	0.62 (0.60–0.64)	0.60 (0.57–0.63)	0.65
LFCR H/D			
Average (SD)	0.49 (0.04)	0.47 (0.05)	0.44
Median (P ₂₅ –P ₇₅)	0.49 0.49 (0.47–0.52)	0.48 (0.43–0.52)	0.24

Chi-square test: comparison between percentages (LNS, LFCI, tibial slope)

Mann Whitney test: mean/median comparison (LFCR, LFCR H/D)

Table 4 Comparison of variables between groups LFCI greater than or equal to 0.7, and less than 0.7

Evaluated variables	LFCI $\geq 0,7$ n=60 (%)	LFCI $< 0,7$ n=14 (%)	p value
Tibial slope			
≤ 12 graus	52 (86.7)	12 (85.7)	0.93
> 12 graus	8 (13.3)	2 (14.3)	
LFCR			
Average (SD)	0.61 (0.04)	0.61 (0.03)	0.98
Median (P ₂₅ –P ₇₅)	0.61 (0.60–0.64)	0,61 (0.59–0.64)	0.82
LFCR H/D			
Average (SD)	0,49 (0,04)	0,47 (0.05)	0.20
Median (P ₂₅ –P ₇₅)	0.49 (0.47–0.52)	0.47 (0.43–0.49)	0.04

Chi-square test: comparison between percentages (LNS, LFCI, tibial slope)

Mann Whitney test: mean/median comparison (LFCR, LFCR H/D)

effect of these issues may contribute to a greater risk of rotational instability, since an increased lateral femoral condylar ratio and a decreased lateral femoral condylar height/depth

ratio are associated with a lateral femoral condyle (LFC) that is more oval in shape and has an increased diameter, which can change the mechanics of the knee by changing the

Table 5 Comparison of morphological parameters between the group with a combined lesion of the lateral meniscus and LNS greater than 2 millimeters, and the group without this association

Evaluated variables	Group 01*n=69 (%)	Group 02**n=5 (%)	p value
Tibial slope			
≤ 12 graus	60 (87.0)	4 (80.0)	0.52
> 12 graus	9 (13.0)	1 (20.0)	
LFCI			
≥ 0,7	56 (81.2)	4 (80.0)	0.95
< 0,7	13 (18.8)	1 (20.0)	
LFCR			
Average (SD)	0.61 (0.04)	0,60 (0,05)	0.56
Median (P ₂₅ –P ₇₅)	0.61 (0.60–0.64)	0,62 (0,54–0,64)	0.67
LFCR H/D			
Average (SD)	0.49 (0.04)	0,47 (0,07)	0.64
Median (P ₂₅ –P ₇₅)	0.49 (0.47–0.51)	0,46 (0,41–0,54)	0.04

* Group 01: Without lateral meniscus lesion and LNS ≤ 2 mm

** Group 02: With lateral meniscus lesion and LNS > 2 mm

Chi-square test: comparison between percentages (LNS, LFCI, tibial slope)

Mann Whitney test: mean/median comparison (LFCR, LFCR H/D)

femoral excursion radius during flexion–extension, causing less tension in the lateral stabilizer structures at low flexion angles, causing damage to the secondary stabilizer support of the ACL. A rare similar study tried to clarify, using lateral radiographs instead, if different methods of quantifying lateral femoral condyle bone morphology were risk factors for ACL injury, and no clinically relevant correlation between the different quantitative measurement methods of the LFC bone morphology in ACL-injured patients, considering the different ratios as individual risk factors [23].

Although 17.5% of our patients had an increased tibial slope, we did not find a significant association between the tibial slope and other evaluated parameters. An increased tibial slope is directly related to a higher risk of primary ACL injury, increased instability in the knee with ACL injury [24], and early failure of ACL reconstruction [9, 14, 24–27]. However, the lack of association with factors indicative of rotational instability (lateral meniscal injury and LNS > 2 mm) aligns with recent literature. It has been demonstrated that the tibial slope significantly increases anterior tibial translation in a static and dynamic way in knees with ACL injury, but is not associated with features in pivot shift [28]. The non-association with LFCI, LFCR, and LFCR H/D can be explained because these parameters analyze alterations in femoral shape. Therefore, a knee would not necessarily present a combined alteration of both the femur and tibia.

The assessment by a single observer, a knee surgeon, of the measurements taken in the study was recently validated

in a similar way [3, 9, 12, 14], despite possible measurement bias. To strengthen our work, all MRI exams were performed with the same acquisition technique on the same imaging device, unlike most cited studies, which used multicenter images with different devices, imaging methods, and protocols.

One limitation of this study is the absence of quantitative pivot shift assessments for comparing preoperative objective instability between groups with and without morphological abnormalities. While such assessments would offer a valuable alternative, their implementation was not feasible in this retrospective study due to the lack of available data from specialized, high-cost devices. It is important to make it clear that the non-spherical femoral condyle is associated with an exacerbated mechanism of rotational instability due to features in the knee flexion radius during the range of motion.

Despite the limitations, we find it relevant that this is a rare study that evaluated, in the same population and with the same pattern of image acquisition, LNS stratified by depth, LFCI, LFCR, LFCR H/D, tibial slope, and the presence of lateral meniscus injury. We significantly found the associations below:

- Elevated rotatory instability criterion (LNS > 2 mm) and:
 - Non-spherical femoral condyles (LFCI < 0.7) (*p* 0.03)
 - Lateral meniscus injury (*p* 0.03)
- LNS > 2 mm + lateral meniscus injury and:
 - Deep lateral femoral condyles (decreased LFCR H/D) (*p* 0.04)
- Morphological features to each other:
 - Non-spherical femoral condyle (decreased LFCI) and decreased median LFCR H/D (deep lateral femoral condyle) (*p* 0.04)

Conclusion

Our findings demonstrate a significant association between a deep lateral femoral notch sign (LNS > 2 mm), lateral meniscal injury, and non-spherical lateral femoral condyles (LFCI < 0.7) in ACL-deficient knees. Furthermore, knees exhibiting both lateral meniscus lesions and a deep LNS (> 2 mm) are associated with decreased median values of LFCR H/D, indicative of deeper femoral condyles. These

associations, building on the established principle that lateral meniscus injury and a deep LNS are indicative of increased rotational instability, prompt us to consider the potential of incorporating femoral shape as a predictive factor for rotational instability. This could lead to a novel criterion for extra-articular augmentation strategies, potentially mitigating the risk of ACL-R failure. Future studies should investigate the predictive value of these combined morphological features in larger cohorts and explore their utility in guiding personalized ACL reconstruction techniques.

Author contribution TC: study conception, data collection, manuscript writing, review, and approval of the final version. AMV: manuscript writing, review, and approval of the final version. AG: manuscript writing, review, and approval of the final version. SZ: manuscript writing, review, and approval of the final version. EBS: manuscript writing, review, and approval of the final version. RSPA: study conception, data collection, manuscript writing, review, and approval of the final version.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

Consent for publication Not applicable.

Human ethics and consent to participate This study #36294820.9.0000.5273 was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Research Ethics Committee of the National Institute of Traumatology and Orthopedics (approval protocol #4.270.990). Participants gave written consent to participate in the study by signing an informed consent form.

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