



Evaluation of Intercondylar Notch and Tibial Slope Angles in Relation to Anterior Cruciate Ligament Injury: A Retrospective MRI Study in a Turkish Population

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Abstract

Aim: Intrinsic variations in knee anatomy, including the intercondylar notch and tibial slope morphology, are associated with anterior cruciate ligament (ACL) injury risk. This study aimed to evaluate the association between the intercondylar notch angle (INA), medial and lateral tibial slope angles MTSA and LTSA, and femoral notch width (FNW) and the occurrence of ACL rupture by comparing patients with ACL injury and healthy controls.

Methods: This retrospective study included 413 individuals aged 20-40 years who underwent knee magnetic resonance imaging (MRI) between January 2016 and November 2019. The study group comprised 232 patients with complete ACL rupture, and 181 healthy individuals without ACL tears served as controls. Morphometric parameters, including the INA, MTSA and LTSA, FNW, intercondylar width (ICW), and notch width ratio (NWR), were measured and compared between groups. The NWR was calculated as FNW/ICW and classified as ≤ 0.27 or > 0.27 . Knees were also categorized by notch shape (A, U, W), and associations with age and sex were analyzed.

Results: The mean INA and FNW were significantly lower, while the LTSA was significantly higher in the ACL rupture group than in controls ($p < 0.01$). The NWR was also significantly lower in the ACL group ($p < 0.001$). An NWR ≤ 0.27 was associated with a 2.24-fold increased risk of ACL rupture, with an area under the curve of 0.724, indicating moderate diagnostic accuracy. No significant difference in notch shape types (A, U, W) was observed between groups ($p = 0.169$).

Conclusion: Reduced notch dimensions, a lower NW ratio, and a steeper lateral tibial slope are significant anatomical risk factors for ACL rupture. Incorporating these MRI-based morphometric parameters into prevention programs may aid early identification of high-risk individuals. Prospective biomechanical studies are warranted to validate these findings and guide individualized prevention strategies.

Keywords: Anterior cruciate ligament injuries, knee joint, magnetic resonance imaging, risk factors

Introduction

The knee is the body's largest synovial joint, formed by the femoral condyles and tibial plateau, with the menisci positioned between them. Stability of the knee depends on static structures such as the capsule, menisci, and ligaments, as well as dynamic support from muscles and

tendons. The anterior cruciate ligament (ACL), one of the primary stabilizers, lies within the joint capsule but outside the synovial membrane and consists of two bundles: the anteromedial and posterolateral (1-3).

Injuries to the ACL represent one of the most prevalent forms of knee pathology, particularly among athletes

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participating in sports that involve cutting, pivoting, or physical contact. The ACL is a primary stabilizer of the knee, preventing anterior displacement and excessive internal rotation of the tibia. Rupture typically occurs during sudden deceleration or rotational loading of the joint (4-6). Numerous factors have been proposed to influence susceptibility to ACL injury, encompassing hormonal, genetic, biomechanical, and anatomical components. Among these parameters, decreased intercondylar notch dimensions and a steeper posterior tibial slope are regarded as important contributors to ligament rupture risk (7-9).

Magnetic resonance imaging (MRI), particularly T2-weighted and proton density (PD)-weighted sequences, plays a crucial role in the evaluation of ACL integrity. The ligament should be examined in sagittal, coronal, and axial planes, with attention to both primary and secondary signs of injury (10,11). Recent studies have highlighted the importance of intrinsic anatomical variations, particularly notch geometry and tibial slope, as key determinants of ACL injury risk (12,13). These morphometric parameters can be quantitatively assessed on MRI, providing valuable insights into the anatomical predisposition to ligament rupture.

We hypothesized that distinct morphological features of the knee joint may contribute to an increased susceptibility to ACL injury. Therefore, the present study aimed to investigate the relationship between the intercondylar notch angle (INA), medial tibial slope angle (MTSA) and lateral tibial slope angle (LTSA), and femoral notch width (FNW), and the occurrence of ACL rupture. By comparing these morphometric parameters between patients with ACL injury and healthy controls, we sought to identify anatomical features that may serve as potential predictive risk factors and contribute to more targeted prevention and individualized screening strategies.

Materials and Methods

Patient Selection

This retrospective cross-sectional study was conducted by reviewing knee MRIs acquired between January 1, 2016, and November 15, 2019, following approval approved by the Ethics Committee of University of Health Sciences Türkiye, İstanbul Haseki Training and Research Hospital (approval no.: 2020-22, date: 12.02.2020). A total of 413 participants were included in the study, comprising 232 patients with complete ACL ruptures and 181 healthy controls. All patients in the study group had complete ACL ruptures. The control group consisted entirely of individuals with no evidence of partial or complete ACL tears on knee MRI, exhibiting healthy knee morphology with intact ligamentous and osseous

structures. In both the study and control groups, male and female participants aged between 20 and 40 years were included. Individuals younger than 20 or older than 40 years were excluded from the study. Those within this age range who had any history of knee ligament injury, previous knee surgery, knee deformities (genu varum or valgum), fractures involving the femur or tibia, or radiological evidence of osteoarthritis were also excluded. According to these criteria, 72 participants were excluded from the initial cohort.

Data Acquisition

Knee MRI scans were obtained using a 1.5-T MRI system (Achieva, Philips Medical Systems, The Netherlands). During image acquisition, patients were positioned supine with the knee in approximately 15 ° flexion and 10 ° external rotation. The knee imaging protocol was as follows:

- Sagittal T1-weighted (T1W): echo time (TE)=20 ms, repetition time (TR)=468 ms, matrix=240 × 284, field of view (FOV)=160 mm, number of excitations (NEX)=1
- Axial plane PD: TE=30 ms, TR=2300 ms, matrix=120 × 152, FOV=150 mm, NEX=1
- Coronal PD: TE=30 ms, TR=2300 ms, matrix=120 × 152, FOV=170 mm, NEX=1
- Sagittal PD: TE=30 ms, TR=2300 ms, matrix=120 × 160, FOV=180 mm, NEX=1

The slice thickness was set to 3 mm with an interslice gap of 0.5 mm.

Image Analysis

The ACL was anatomically evaluated in axial, coronal, and sagittal MRI sections. For each patient, age, sex, and the side of the knee assessed were recorded.

On sagittal T1W images, the INA was measured according to the approach proposed by Huang et al. (8). The INA was defined as the angle between the line drawn parallel to the femoral axis and the Blumensaat line tangent to the roof of the intercondylar notch (Figure 1).

On sagittal T1W images, the MTSA was measured as the angle between a line drawn perpendicular to the tibial axis and a line connecting the anterior and posterior peaks of the medial tibial plateau in its central section. This section is identified as the one where the tibiofemoral joint space is narrowest (Figure 2). Similarly, the LTSA was measured in the central section of the lateral tibial plateau, following the method described by Stijak et al. (9) (Figure 3).

Each measurement was performed three times for the same subject, and the mean value was used for analysis. The relationships between ACL injury risk and INA, MTSA, LTSA, sex, and age were then evaluated.

On axial PD images at the level of the popliteal groove and parallel to the line joining the posterior borders of

the femoral condyles, the intercondylar width (ICW) and FNW were measured according to the method described by Bouras et al. (14) (Figure 4). The notch width (NW) ratio was calculated as FNW/ICW .

On axial PD fat-suppressed images, the femoral notch morphology was classified as Type A, Type U, or Type W, following the criteria defined by van Eck et al. (15) (Figure 5). Type A notches were characterized by a narrowing configuration from the midsection toward the base and apex, reflecting a stenotic morphology. Type U notches

exhibited a broader outline without tapering in the midsection, whereas Type W notches represented a wider variant of Type U, characterized by two distinct apices instead of a flat roof.

Subsequent analyses investigated which notch type was more frequently associated with ACL rupture and whether a significantly increased risk was observed in patients with narrow FNW or an NW ratio ≤ 0.27 . The relationships between these morphological parameters, age, and sex were also evaluated.

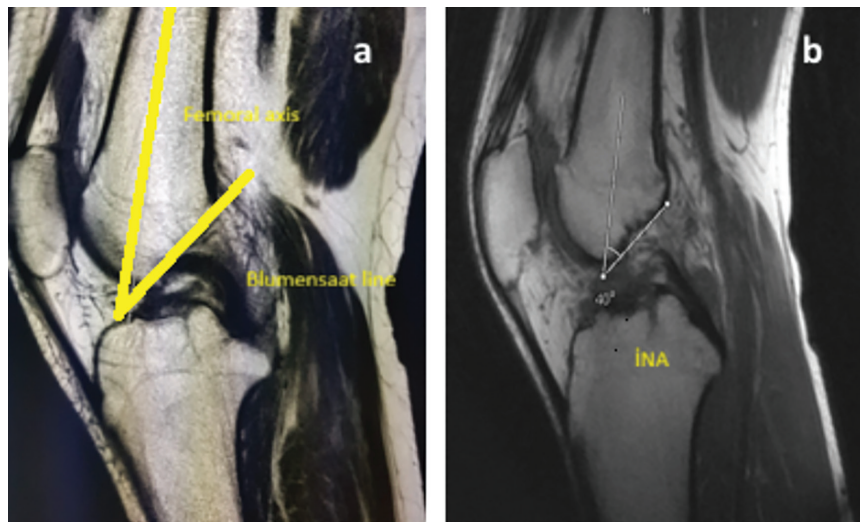


Figure 1. Measurement of the intercondylar notch angle. Sagittal T1-weighted MRI from two different patients show the angle between a line drawn parallel to the femoral axis and the Blumensaat line tangent to the roof of the intercondylar notch. The schematic illustration (a), and a sample patient measurement (b) are shown

MRI: Magnetic resonance imaging, INA: Intercondylar notch angle

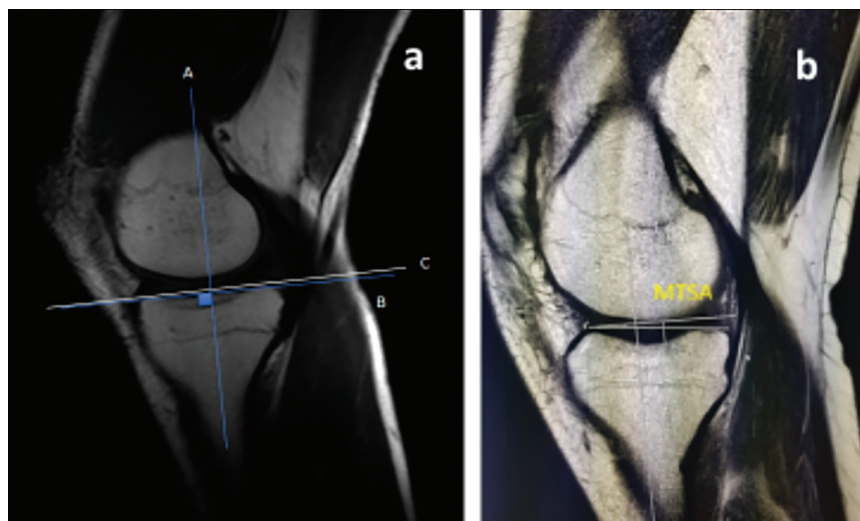


Figure 2. Measurement of the MTSA. On sagittal T1-weighted images, a line parallel to the tibial axis (A), a line perpendicular to the tibial axis (B), and a line connecting the anterior and posterior peaks of the medial tibial plateau in the central section (C) are drawn. The MTSA is defined as the angle between lines B and C. The schematic illustration (a), and a sample patient measurement (b) are shown

MTSA: Medial tibial slope angle

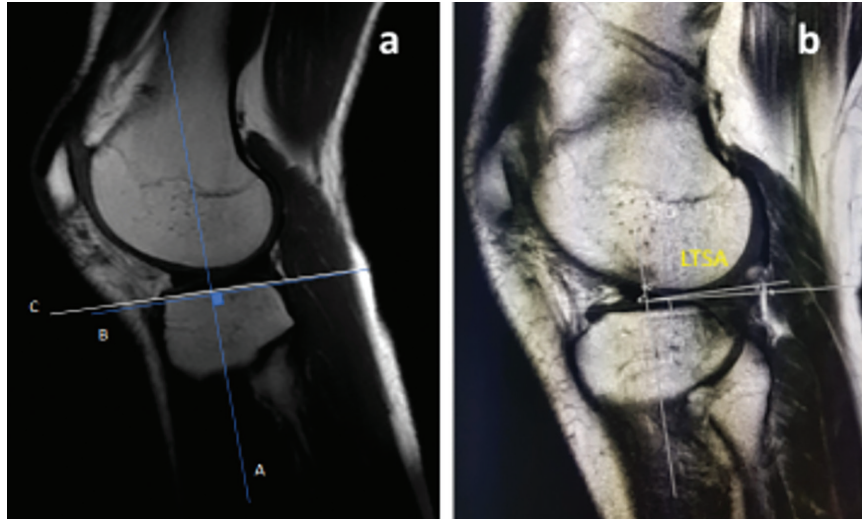


Figure 3. Measurement of the LTSA. On sagittal T1-weighted images, a line parallel to the tibial axis (A), a line perpendicular to the tibial axis (B), and a line connecting the anterior and posterior peaks of the lateral tibial plateau in the central section (C), are drawn. The LTSA is defined as the angle between lines B and C. The schematic illustration (a) and a sample patient measurement (b) are shown

LTSA: Lateral tibial slope angle

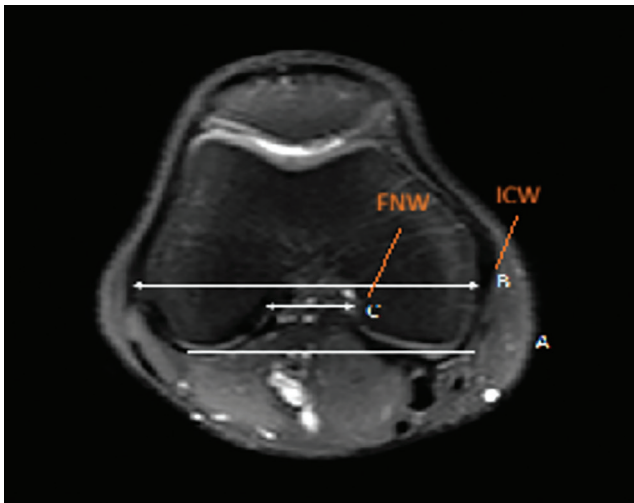


Figure 4. Measurement of femoral intercondylar notch width. A reference line is drawn parallel to the posterior borders of the femoral condyles (A) on an axial PD image passing through the popliteal groove. The intercondylar width (B) and the femoral notch width (C) are measured, and the notch width ratio is calculated as C/B

PD: Proton density, FNW: Femoral notch width, ICW: Intercondylar width

Statistical Analysis

All statistical analyses were performed using Number Cruncher Statistical System 2007 Statistical Software (Utah, USA). Descriptive statistics, including mean, standard deviation, median, and interquartile range, were calculated for all variables. The Shapiro-Wilk test was used to assess the normality of data distribution.

For comparisons between two independent groups, the independent samples t-test was applied to normally distributed variables, while the Mann-Whitney U test was used for non-normally distributed variables. The chi-square test was used to compare categorical data. Relationships between continuous variables were evaluated using the Pearson correlation test.

To determine the independent predictors of ACL injury, logistic regression analysis was performed, including variables that were significant in univariate analysis. The receiver operating characteristic (ROC) curve was used to determine the optimal cut-off value, and sensitivity, specificity, positive predictive value (PPV), negative predictive value, and positive likelihood ratio [LR (+)] were calculated.

All statistical results were evaluated at a significance level of $p < 0.05$.

Results

A total of 413 individuals aged 20-40 years were evaluated, including 232 patients with complete ACL rupture (198 males, 34 females) and 181 healthy controls (144 males, 37 females). The mean age was 32.27 ± 6.09 years in the study group and 31.30 ± 6.15 years in the control group. The distribution of age, sex, and laterality (right/left knee) between groups was statistically homogeneous.

In the study group, 126 (54.3%) MRIs were of the right knee and 106 (45.7%) of the left; in the control group, 83 (45.9%) were of the right and 98 (54.1%) were of the left.

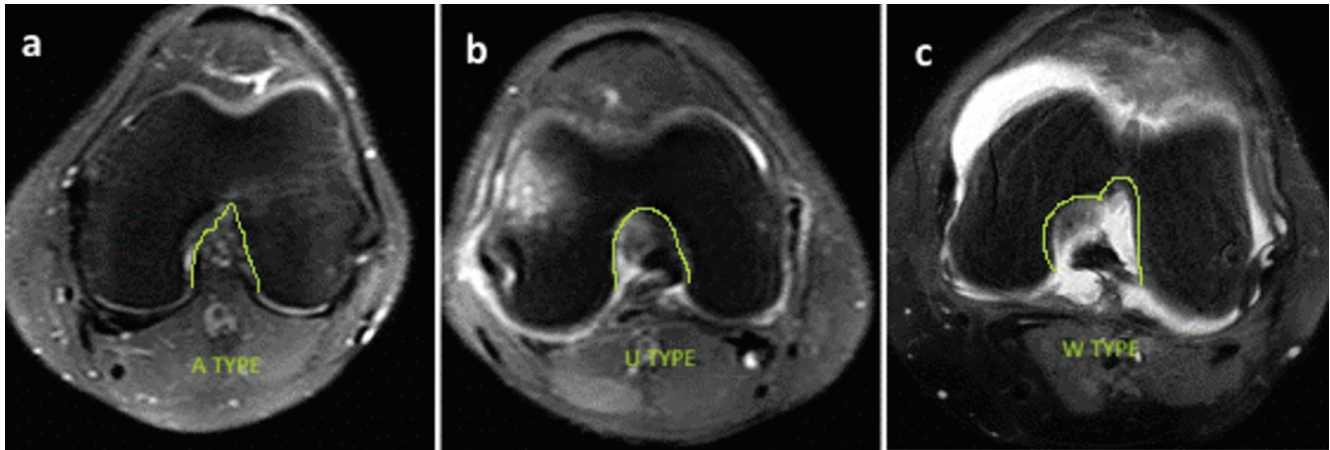


Figure 5. Classification of femoral notch shape on axial PD FS images. Knees were categorized into three types based on the notch configuration: type A, type U, and type W

PD: Proton Density, FS: Fat-Suppressed

The mean INA was significantly lower in the study group compared with controls ($p=0.0001$). LTSA values were significantly higher in the study group ($p=0.002$), while no significant difference was found in MTSA values ($p=0.419$) (Table 1).

The mean FNW was significantly lower ($p=0.0001$), and the mean ICW was significantly higher ($p=0.036$) in the study group compared with controls. The (NWR=FNW/ICW) was also significantly lower in the study group ($p=0.0001$). No significant difference was observed in knee notch shape types (A, U, W) between groups ($p=0.169$) (Table 1).

A significant negative correlation was detected between age and MTSA in the study group ($r=-0.153$, $p=0.020$) (Table 2).

Among the measured parameters, the NWR showed the highest diagnostic accuracy for ACL injury, with an area under the ROC curve (AUC) of 0.724 (0.678-0.767) (Table 3). For a cut-off of NWR ≤ 0.27 , sensitivity was 69.4%, specificity 69.06%, PPV 74.2%, and LR (+) 2.24 (Table 4).

Overall, patients with low INA, high LTSA, narrow FNW, and NWR ≤ 0.27 had a significantly increased risk of ACL rupture (Table 5).

Table 1. Study and control group INA, MTSA, LTSA, FNW, ICW, NWR, and type comparison

		Control group n=181		Study group n=232		p
INA	Mean ± SD	39.2±3.81		36.93±4.56		0.0001*
MTSA	Mean ± SD	3.32±2.46		3.38±2.31		0.419‡
	Median (IQR)	3 (1-5)		3 (2-5)		
LTSA	Mean ± SD	3.42±2.26		4.44±3.17		0.002‡
	Median (IQR)	3 (2-5)		4 (2-6)		
FNW	Mean ± SD	2.33±0.26		2.16±0.25		0.0001*
ICW	Mean ± SD	7.98±0.55		8.09±0.55		0.036*
NWR	Mean ± SD	0.29±0.03		0.26±0.03		0.0001*
NWR	>0.27 NWR	125	69.06%	71	30.60%	0.0001+
	≤0.27 NWR	56	30.94%	161	69.40%	
Type	A Type	116	64.09%	130	56.03%	0.169+
	U Type	53	29.28%	77	33.19%	
	W Type	12	6.63%	25	10.78%	

*:Independent t-test ‡:Mann Whitney U test +:Chi-square test

INA: Intercondylar notch angle, MTSA: Medial tibial slope angle, LTSA: Lateral tibial slope angle, FNW: Femoral notch width, ICW: Intercondylar width, NWR: Notch width ratio, SD: Standard deviation, IQR: Interquartile range

Table 2. Pearson correlation test

		Control group	Study group
		Age	Age
INA	r	0.112	0.045
	p	0.134	0.494
MTSA	r	0.124	-0.153
	p	0.096	0.020
LTSA	r	-0.086	-0.057
	p	0.251	0.388
FNW	r	-0.229	-0.075
	p	0.002	0.256
ICW	r	-0.265	-0.037
	p	0.0001	0.577
NWR	r	-0.084	-0.005
	p	0.260	0.934

p: Significance value, r: Correlation coefficient

INA: Intercondylar notch angle, MTSA: Medial tibial slope angle, LTSA: Lateral tibial slope angle, FNW: Femoral notch width, ICW: Intercondylar width, NWR: Notch width ratio

Table 3. Area under the ROC curve

	AUC	SE	95% CI
NWR	0.724	0.025	0.678-0.767
FNW	0.678	0.027	0.630-0.723
INA	0.647	0.028	0.599-0.693
LTSA	0.588	0.028	0.539-0.636
ICW	0.558	0.028	0.509-0.607

ROC: Receiver operating characteristic, AUC: Area under the curve, SE: Standard error, CI: Confidence interval, NWR: Notch width ratio, FNW: Femoral notch width, INA: Intercondylar notch angle, LTSA: Lateral tibial slope angle, ICW: Intercondylar width

Table 4. Cut-off points in the differential diagnosis of ACL injury by variables

	Predictive value	Sensitivity	Specificity	PPV	NPV	LR (+)
NWR	≤0.27	69.40	69.06	74.2	63.8	2.24
FNW	≤2.21	56.47	69.06	70.1	55.3	1.83
INA	≤38	64.22	60.77	67.7	57.0	1.64
LTSA	>3	55.17	62.43	65.3	52.1	1.47
ICW	>7.83	71.98	38.67	60.1	51.9	1.17

ACL: Anterior cruciate ligament, PPV: Positive predictive value, NPV: Negative predictive value, LR: Likelihood ratio, NWR: Notch width ratio, FNW: Femoral notch width, INA: Intercondylar notch angle, LTSA: Lateral tibial slope angle, ICW: Intercondylar width

Table 5. Logistic regression analysis to determine the factors affecting ACL injury

	B	P	OR	OR (95% CI)	
				Lower bound	Upper bound
INA	-0.12	0.0001	0.89	0.84	0.94
LTSA	0.15	0.0001	1.16	1.07	1.25
FNW	-1.31	0.021	0.27	0.09	0.82
NWR (≤0.27)	-1.06	0.0001	0.35	0.20	0.61

ACL: Anterior cruciate ligament, B: Beta coefficient, P: Significance value, OR: Odds ratio, CI: Confidence interval, INA: Intercondylar notch angle, LTSA: Lateral tibial slope angle, FNW: Femoral notch width, NWR: Notch width ratio

Discussion

Increasing evidence suggests that intrinsic knee morphology plays a significant role in determining the risk of ACL injury. Several morphometric parameters, including the INA, MTSA and LTSA, FNW, ICW, and the NWR, have been extensively investigated as potential anatomical predictors of ACL rupture. Among these, the NWR, defined as the ratio of FNW to ICW, is regarded as one of the most reliable indicators, as it reflects the spatial capacity of the femoral notch to accommodate the ACL. A reduced NWR may limit the available space for the ligament, predisposing it to impingement and increased mechanical stress during knee motion.

In this study, we found that the INA and FNW were significantly lower, whereas the LTSA was significantly higher in patients with ACL rupture compared with healthy controls. No significant difference was observed in the MTSA between the groups. These findings support the hypothesis that morphological narrowing of the femoral notch and steeper tibial slopes increase ACL vulnerability by altering joint biomechanics. Our results are consistent with those reported by Huang et al. (8), who demonstrated significantly lower INA and higher LTSA values in patients with ACL injuries. Similarly, Dejour and Bonnin (16), as well as Khan et al. (17), emphasized that an increased lateral tibial slope promotes greater anterior tibial translation, thereby predisposing the ACL to excessive tensile stress and rupture.

These observations further emphasize the importance of notch geometry and tibial slope as key structural determinants of ACL integrity. In the present study, the NWR emerged as the strongest predictor of ACL injury,

with an area under the ROC curve of 0.724 and an odds ratio indicating a 2.24-fold increased risk among subjects with an NWR ≤ 0.27 . These findings are consistent with the results of Souryal and Freeman (18) as well as the study by Anderson et al. (19), who identified an NWR below 0.27 as a critical threshold associated with greater injury risk. Similarly, Bouras et al. (14) reported that a narrow femoral notch and low NWR were significantly correlated with increased ACL rupture incidence, particularly in knees exhibiting type A notch morphology. Although the overall distribution of notch shapes (A, U, W) did not differ significantly between groups in our cohort, the proportion of type A knees was higher among patients with an NWR ≤ 0.27 , further reinforcing the association between notch stenosis and ACL injury risk.

Our findings regarding the LTSA further corroborate previous evidence indicating that a steeper lateral tibial plateau increases anterior tibial translation under axial loading, thereby heightening stress on the ACL during pivoting or deceleration movements (20-22). Stijak et al. (9) similarly reported that a more vertical lateral tibial slope represents a key morphometric feature in patients with ACL rupture. Although no significant association was found between the MTSA and ACL injury, a significant negative correlation between age and MTSA was observed within the study group. This finding may reflect age-related adaptations in tibial geometry; however, its clinical relevance remains to be clarified.

Gender-based analyses in previous research have produced variable results. Hashemi et al. (23,24) reported that women with increased lateral tibial slope angles and decreased medial tibial depth are more susceptible to ACL injury, whereas men exhibit risk patterns associated with concomitant increases in both medial and LTSA. In the present study, no significant sex-based differences in ACL injury risk were identified, consistent with the findings of Vrooijink et al. (25) and van Diek et al. (26). However, both FNW and ICW values were lower in women than in men, suggesting that female knees may possess proportionally narrower intercondylar spaces despite similar NW ratios. Further investigations with larger female cohorts are warranted to elucidate potential gender-specific anatomical risk factors for ACL injury.

Several studies have explored the association between body mass index (BMI) and ACL injury risk, as increased body weight may influence tibial slope geometry and elevate knee joint loading (27,28). Although BMI data were not available in our retrospective cohort, this parameter may affect tibial plateau morphology and warrants further investigation. In addition, the absence of contralateral knee imaging limited our ability to evaluate potential bilateral or genetic predispositions, which have

been proposed as contributing factors to ACL rupture (19,29).

In line with previous reports, our findings confirm that reduced intercondylar notch dimensions and an increased lateral tibial slope represent significant intrinsic risk factors for ACL rupture (30,31). Although non-contact ACL injuries, which account for the majority of cases and are multifactorial in origin, morphological narrowing of the intercondylar notch appears to play a consistent and reproducible role across different populations (32).

Study Limitations

There are certain limitations that should be considered when interpreting the findings of this study. Its retrospective design precludes causal inference, and the absence of data on BMI, activity level, and trauma mechanism reduces the generalizability of the findings. Furthermore, the lack of contralateral knee imaging prevented evaluation of potential bilateral or genetic predispositions, and minor variations in MRI acquisition parameters may have introduced measurement variability. Only patients with complete ACL ruptures were included, thereby excluding partial injuries that may exhibit different anatomical characteristics. Despite these limitations, the relatively large sample size and the use of a standardized measurement protocol enhance the reliability and robustness of our results.

Conclusion

In summary, our findings demonstrate that a smaller INA, reduced FNW, lower NWR, and steeper lateral tibial slope are significant morphological risk factors for ACL rupture. These findings suggest that intrinsic knee morphology plays a key role in injury susceptibility, independent of external factors such as sport type or trauma mechanism. Quantitative evaluation of these parameters on MRI may enhance injury risk prediction and support the development of targeted prevention strategies. Future prospective, multicenter, and biomechanical studies incorporating body composition and activity data are warranted to further elucidate the complex interplay between intrinsic anatomy and ACL injury susceptibility.

Ethics

Ethics Committee Approval: The study was approved by the Ethics Committee of University of Health Sciences Türkiye, Istanbul Haseki Training and Research Hospital (approval date: 12.02.2020, approval number: 2020-22). All procedures performed in studies involving human participants were conducted in accordance with the ethical standards of the institutional research committee and with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

Informed Consent: Written informed consent was obtained from all participants before undergoing magnetic resonance imaging.

Footnotes

Authorship Contributions

Surgical and Medical Practices: E.C., R.K., Concept: E.C., T.I., Design: E.C., T.I., Data Collection or Processing: E.C., R.K., Analysis or Interpretation: E.C., T.I., R.K., Y.S., Literature Search: E.C., Writing: E.C.

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