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MRI MORPHOLOGICAL ANALYSIS OF FEMORAL INTERCONDYLAR NOTCH IN HEALTHY PARTICIPANTS IN SOUTHWEST CHINA

Junqing Liang[1, 2], Fong Fong Liew[3*]

[1] Faculty of Medicine, MAHSA University, Jenjarom, Selangor, Malaysia.
[2] Department of Joint Surgery, The People's Hospital of Baise, Guang Xi, China.
[3] Department of Preclinical Science, Faculty of Dentistry, MAHSA University, Jenjarom, Selangor, Malaysia.

Corresponding Author(s): Fong Fong Liew fflew@mahsa.edu.my

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Abstract

Anterior cruciate ligament (ACL) injury is a prevalent knee joint issue influenced by femoral intercondylar notch morphology. This study evaluates intercondylar notch parameters in healthy participants using MRI to establish reference values for assessing ACL injury risk. MRI scans of 240 healthy participants were analyzed to measure femoral intercondylar notch parameters. These parameters, including axial notch width index (NWI1), coronal notch width index (NWI2), coronal notch width index at the posterior cruciate ligament tibial attachment point (NWI3), axial notch shape index (NSI1), coronal notch shape index (NSI2), axial cross-sectional area (CSA1) and coronal cross-sectional area (CSA2), were calculated. Gender differences were analyzed using t-tests or Mann-Whitney U tests, and reference values were derived. No significant gender differences were observed for NWI1, NWI2, NSI1 and NSI2. Gender differences were found in the intercondylar notch cross-sectional areas in both axial and coronal planes, as well as in NWI3. Effective ACL injury prevention should consider individual skeletal structure differences and adopt personalized strategies. Preoperative assessment is crucial for determining the necessity of intercondylar notch plasty and aids in developing more precise treatment plans.

Keywords: Anterior cruciate ligament injury, intercondylar notch, MRI, Notch Width Index, Notch Shape Index, Cross-sectional area.

1. Introduction

The intercondylar notch is a key anatomical structure in the knee joint. Its primary function is to house the anterior cruciate ligament (ACL) and the posterior cruciate ligament (PCL), playing a crucial role in maintaining knee joint stability and normal function (Kayani et al., 2020; Korolev et al., 2020; Lam et al., 2009). The morphology and size of the intercondylar notch vary depending on factors such as an individual's gender, age, genetics and activity levels. Significant differences may also exist among different populations (Dwivedi et al., 2022; Phombut et al., 2021; S, 2021). In recent years, with the advancement of research on knee joint-related diseases, the anatomical characteristics of the intercondylar notch have garnered increasing attention. Research shows that changes in the shape and size of the intercondylar notch can increase the risk of problems such as intercondylar notch impingement syndrome, ACL injuries and knee osteoarthritis (KOA). These abnormalities can have a potential impact on clinical manifestations such as pain, joint instability and restricted mobility. A narrow intercondylar notch increases the risk of ACL injuries, which can cause damage to ligaments, wear on cartilage and lead to osteoarthritis (Hirtler et al., 2022).

Researchers currently study intercondylar notch morphology using methods such as anatomical observation, imaging measurements and biomechanical analysis (Agrawal et al., 2021; Chen et al., 2023; Keremu et al., 2020; Li et al., 2018; Oshima et al., 2020). However, due to differences in samples and methodologies, conclusions remain inconsistent and baseline data for healthy populations are still limited (Dwivedi et al., 2022; Phombut et al., 2021; S, 2021). Magnetic resonance imaging (MRI) is a non-invasive imaging technique with high resolution and specificity that can accurately evaluate soft tissues and bony structures of the knee joint. MRI measurements match well with anatomical data, which is why it is commonly used to study the shape of the intercondylar notch (Akgün, 2020; Chen et al., 2016; Hirtler et al., 2022).

This study aims to comprehensively measure and analyze the morphological characteristics of the intercondylar notch in healthy populations using MRI technology. By measuring parameters such as the width, depth and area of the notch, and incorporating gender-based analysis, the study seeks to explore the distribution patterns across different populations. The results will offer valuable information about the causes of ACL injuries, the problem of intercondylar notch impingement syndrome and knee osteoarthritis. Additionally, the results will offer data support for developing individualized prevention strategies in clinical practice and promoting early diagnosis and intervention for knee joint-related diseases.

2. Methodology

2.1 Sample Selection

This study was conducted in Baise City, China and its surrounding areas, a region with a culturally diverse population, including Zhuang and Han ethnic groups. A random sampling method was used to ensure data representativeness and scientific validity. The study included 240 healthy participants (120 males and 120 females) aged 18–60 years who underwent MRI scans at Baise People’s Hospital between November 2021 and April 2024.

2.1.1 Exclusion Criteria

Participants were excluded from the study if they had a history of knee joint trauma or surgery, were pregnant or breastfeeding, could not cooperate with imaging examinations, had knee arthritis or other structural abnormalities, were using medications or undergoing treatments that could affect knee structure, had congenital knee deformities or diseases, or had severe chronic illnesses or systemic conditions impacting knee health.

By excluding individuals with prior knee injuries or surgeries, this research aimed to minimize confounding factors and enable a clearer analysis of the intercondylar notch's natural morphology and its relationship with ACL injury risk. This approach strengthened the study's scientific rigor and credibility.

2.1.2 Ethical Considerations

The Research Management Centre, MAHSA University (RMC/JUN/2024/EC05) and the ethics committee of Baise People's Hospital (approval number: KY2024053001) approved the study. Prior to participation, all individuals provided informed consent after being fully briefed on the study's objectives and procedures. Strict measures were taken to safeguard participant privacy and ensure data confidentiality throughout the research process.

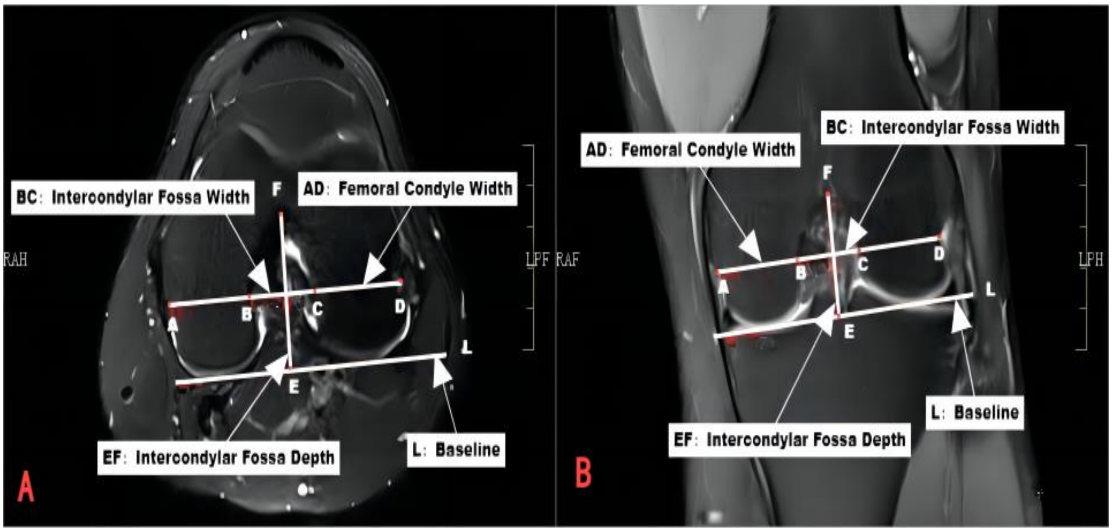
2.1.3 Study Design and Execution

This case-control study recruited participants through established channels, specifically the hospital's patient database. The research team fostered trust and maintained effective communication with participants to ensure comprehensive and accurate data collection. Advanced MRI imaging technology and a highly skilled medical team ensured the reliability and precision of the measurements.

2.2 MRI Scanning

Participants were positioned supine on the examination table and knee joint MRI scans were performed using a Siemens Magnetom Skyra 3.0T scanner with a 15-channel knee coil. Axial images were acquired using a proton density fat-saturated turbo spin echo (PD-TSE-FS-TRA) sequence with the following parameters: TR 4200 ms, TE 72 ms, field of view (FOV) 320 mm and slice thickness 3 mm. Coronal images were obtained using a proton density fat-saturated turbo spin echo (PD-TSE-COR-P2_320_FS) sequence with the following parameters: TR 1800 ms, TE 20 ms, FOV 320 mm and slice thickness 4 mm. The scanned images were imported into the Siemens Syngovia workstation with MPR software for measurements. Data recorded included axial and coronal intercondylar notch widths, femoral condyle width and notch depth (Li et al., 2018).

The intercondylar notch width index, notch shape index and cross-sectional area were determined for the entire study population and analyzed separately for male and female groups.



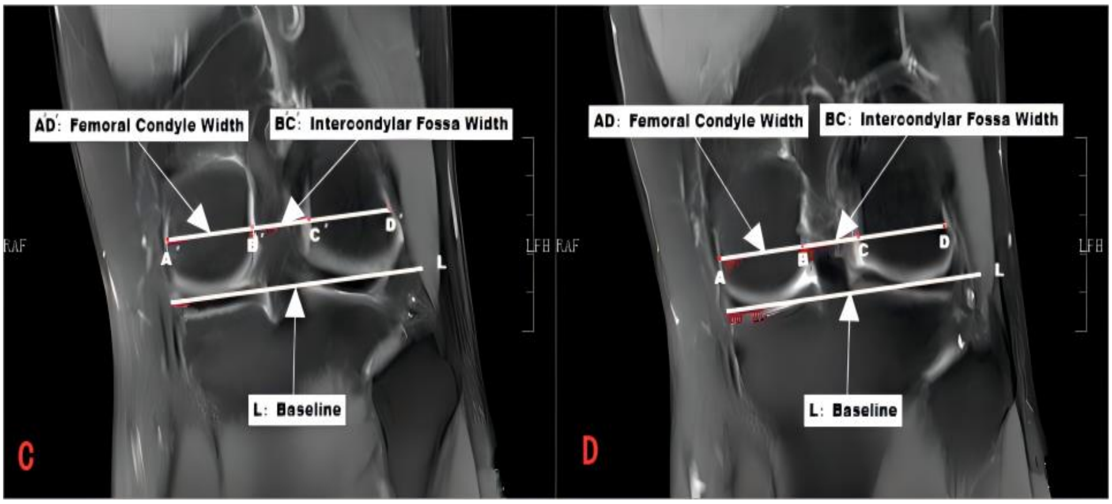


Figure 1. (A) Axial view schematic diagram for intercondylar notch measurement; (B) Sagittal view (at the popliteus tendon groove level) schematic diagram for intercondylar notch measurement; (C) Sagittal view (anterior to the posterior cruciate ligament insertion) schematic diagram for intercondylar notch measurement; (D) Sagittal view (at the posterior cruciate ligament tibial insertion level) schematic diagram for intercondylar notch measurement (MRI images were obtained from the Radiology Department of Baise People's Hospital and processed using the hospital's outpatient imaging system software).

2.2.1 Notch Width Index (NWI):

The baseline is defined as the line tangent to the cartilage of the medial and lateral femoral condyles (line L in Figure 1A-D). The depth is the vertical distance from the top of the intercondylar notch to the baseline (line EF in Figure 1A-D). A line parallel to line L is drawn through the midpoint of line EF, intersecting the cartilage of the medial and lateral condyles and the medial and lateral walls of the intercondylar notch. These intersecting lines are labeled BC and AD in Figure 1A-D (Xu et al., 2011).

- Axial Notch Width Index (NWI1): The width of the intercondylar notch (BC) and the width of the femoral condyles (AD) were measured at the level of the intertendinous groove on axial MRI or CT images.
  The formula is NWI1 = BC / AD.

- Coronal Notch Width Index (NWI2): The width of the intercondylar notch (BC) and the width of the femoral condyles (AD) were measured at the level of the intertendinous groove on coronal MRI or CT images.
  The formula is NWI2 = BC / AD.

- Coronal (Pre- and At-Posterior Cruciate Ligament Tibial Insertion) Notch Width Index (NWI3): The width of the intercondylar notch (B'C' and BC) and the width of the femoral condyles (A'D' and AD) were measured at the pre-tibial insertion and tibial insertion levels of the posterior cruciate ligament, respectively.
  The formula is NWI3 = (B'C'/A'D' + BC AD)/2.

2.2.2 Notch Shape Index (NSI) (Xu et al., 2011):

- Axial Notch Shape Index (NSI1): The width of the intercondylar notch (BC) and the depth of the intercondylar notch (EF) were measured at the level of the intertendinous groove on axial MRI or CT images.

  The formula is NSI1 = BC / EF.

- **Coronal Notch Shape Index (NSI2):** The width of the intercondylar notch (BC) and the depth of the intercondylar notch (EF) were measured at the level of the intertendinous groove on coronal MRI or CT images.

The formula is NSI2 = BC / EF.

2.2.3 Cross-Sectional Area (CSA) (Xu et al., 2011):

- Axial Cross-Sectional Area (CSA1): The width of the intercondylar notch (BC) and the depth of the notch (EF) were measured at the level of the intertendinous groove on axial MRI or CT images.

The formula is CSA1 = BC*EF (mm^2).

- Coronal Cross-Sectional Area (CSA2): The width of the intercondylar notch (BC) and the depth of the notch (EF) were measured at the level of the intertendinous groove on coronal MRI or CT images.

The formula is CSA2 = BC*EF (mm^2).

2.3 Data Analysis

2.3.1 Gender-based Comparison of MRI Scan Metrics

Seven MRI-derived metrics (NWI1, NSI1, CSA1, NWI2, NSI2, CSA2 and NWI3) were compared between female and male participants. Independent samples t-tests were used for normally distributed data, while Mann-Whitney U tests were used for non-normally distributed data. A p-value < 0.05 indicated statistical significance.

2.3.2 Reference Values for the Intercondylar Notch in Healthy Participants

For normally distributed groups, reference values were calculated as the mean minus 1.64 standard deviations (χ - 1.64 SD). For non-normally distributed groups, reference values were calculated using the 5th percentile (P5).

3. Results

3.1 Demographic Data

Among the 240 healthy participants in the MRI group of this study, there were 120 females and 120 males, with 102 left knees and 138 right knees scanned. The average age was 33.93±7.86 years. Participants were selected using a computer-generated random sampling method to ensure an unbiased representation of the population. Independent samples t-tests showed no significant differences in gender ($p = 0.3$), age ($p = 0.18$) or scan location ($p = 0.65$) within the MRI group (**Table 1**).

Table 1 Epidemiological characteristics of study participants (n=240). No significant differences were observed between groups (t-tests, $p > 0.5$).

Category	**N(%) or mean ± SD**	**P-value**
Sex		
Female	120 (50.00%)	0.30 †
Male	120 (50.00%)	
Age (years)	33.93 ± 7.86	0.18 †
Scan site		
Left knee	102 (42.5%)	0.65 †
Right knee	138 (57.5%)	

† T-test

3.2 Comparison of Indicators Across Different Gender Groups

During the MRI examinations, a total of 7 sets of indicators from female and male groups were compared using a T-test or Mann-Whitney U test. The results showed that 3 sets of indicators had statistically significant differences (all $P < 0.05$), while 4 sets did not show statistically significant differences ($P > 0.05$), as shown in **Table 2**.

Table 2. Hypothesis testing results for different examination methods, comparing female (F) and male (M) groups. (T = t-test; U = Mann-Whitney U test).

	MRI		
	Male (mean ± SD)	**Female (mean ± SD)**	**P-value**
NWI1	0.30 ± 0.03	0.307 ± 0.34	0.164 †
NSI1	0.65 ± 0.08	0.678 ± 0.79	0.459 ‡
CSA1	766.39 ± 128.06	605.42 ± 118.98	<0.001 ‡
NWI2	0.29 ± 0.04	0.291 ± 0.04	0.887 ‡
NSI2	0.72 ± 0.14	0.705 ± 0.09	0.579 ‡
CSA2	646.33 ±145.10	506.294 ± 123.91	<0.001 †
NWI3	0.31 ± 0.03	0.323 ± 0.03	0.029 †

† T-test
‡ Mann-Whitney U test

3.3 Reference Values for Various Indicators of the Intercondylar Notch in Healthy Participants

Analysis of MRI data revealed distinct patterns for different indicators. For NSI1, NWI2 and NSI2, no significant gender-based differences were observed. Due to their skewed distributions and large sample sizes (>100), percentiles were used to calculate reference values for the combined male and female groups.

In contrast, statistically significant gender differences were found for CSA1 and CSA2. For normally distributed indicators (CSA2 in both sexes and CSA1 in males), reference values were determined using the mean minus 1.64 standard deviations. For the skewed distribution of CSA1 in females, percentiles were used to establish reference values.

3.3.1 Groups with Normal Distribution

There are seven groups with a normal distribution. The reference values are calculated using the mean minus 1.64 multiplied by the standard deviation ($\bar{\chi}$ -1.64S) as depicted in **Table 3**.

Table 3. This study establishes reference values for intercondylar notch parameters in healthy participants. Participants were categorized as follows: T-MRI-NWI1 (total MRI scan NWI1 group), F-MRI-NWI3 (total MRI scan NWI3 group, females), F-MRI-CSA2 (total MRI scan CSA2 group, females), M-MRI-CSA1 (total MRI scan CSA1 group, males), M-MRI-CSA2 (total MRI scan CSA2 group, males) and M-MRI-NWI3 (total MRI scan NWI3 group, males). For normally distributed parameters, reference values were calculated using the mean ± 1.64 standard deviations. CSA1 and CSA2 represent area (mm²), while NWI1 and NWI3 are dimensionless comparison values.

	Normal distribution		
	$\bar{\chi}$	**S**	**$\bar{\chi}$-1.64*S***
T-MRI-NWI1	0.30	0.03	0.25
F-MRI-NWI3	0.32	0.03	0.27
F-MRI-CSA2	506.29	123.91	303.08 mm^2
M-MRI-CSA1	766.39	128.06	556.38 mm^2
M-MRI-CSA2	646.32	145.10	408.36 mm^2
M-MRI-NWI3	0.31	0.03	0.26

3.3.2 Reference Values for Skewed Distributions Using the P5 Lower Limit

Reference values for five groups with skewed distributions were calculated using the 5th percentile (P5), as shown in **Table 4**.

Table 4. Reference values for intercondylar notch parameters in healthy participants with skewed distributions. The groups are defined as follows: T-MRI-NSI1 (total MRI scan NSI1 group), T-MRI-NWI2 (total MRI scan NWI2 group), T-MRI-NSI2 (total MRI scan NSI2 group) and F-MRI-CSA1 (female MRI scan CSA1 group).

	Skewed distribution		
	$\bar{\chi}$	S	Percentile (P5)
T-MRI-NSI1	0.65	0.08	0.54
T-MRI-NWI2	0.71	0.12	0.23
T-MRI-NSI2	0.29	0.04	0.58
F-MRI-CSA1	605.42	118.98	428.89 mm^2

4. Discussion

MRI is a vital imaging technology for evaluating the femoral intercondylar notch in healthy participants. With its superior soft tissue contrast, MRI is an ideal tool for studying tissues such as cartilage, tendons and ligaments (Albano et al., 2024; Li et al., 2024). It enables clear visualization of the knee joint's complex structures, including the ACL and its relationship with the intercondylar notch (Nacey et al., 2017) . MRI also allows for multiplanar imaging without radiation exposure, which gives doctors a full picture of knee joint diseases and injuries and helps with diagnosis (Li et al., 2024).

4.1 Notch Width Index (NWI)

When evaluating morphological indicators of intercondylar notch width, the NWI is widely regarded as an effective metric for measuring notch size. Studies have shown that as a relative indicator, NWI demonstrates high consistency in measurements across genders and between bilateral knee joints. This consistency minimizes the impact of measurement errors, enabling a more accurate reflection of the actual width of the intercondylar notch. As a result, NWI holds significant value in clinical applications (Bayer et al., 2020; Domzalski et al., 2010; Shaw et al., 2015).

The results of this study indicate that the axial and coronal NWI measurements (T-MRI-NWI1 and T-MRI-NWI2), obtained at the patellar tendon groove level via MRI, showed no significant gender differences across the overall group, which is consistent with previous findings (Al-Saeed et al., 2012; Bayer et al., 2020; Domzalski et al., 2010; Shaw et al., 2015). However, a significant gender difference was observed in the NWI measurements (MRI-NWI3) obtained on the coronal plane at the posterior cruciate ligament level. There is ongoing debate in the academic community regarding the standard value of NWI. Stein et al. measured the NWI at two-thirds of the intercondylar notch depth on coronal MRI images, reporting an average value of 0.263 ± 0.005 (Stein et al., 2010). Domzalski et al., based on MRI data from 44 normal knees, reported an average NWI value of 0.2691 (Domzalski et al., 2010). In exploring the relationship between intercondylar notch morphology and ACL rupture, Al-Saeed et al., using MRI measurements from 560 participants, suggested that the standard NWI value should be set at 0.270 or above, with values below this threshold potentially indicating a narrowed notch (Al-Saeed et al., 2012).

In this study, the reference value for T-MRI-NWI1 in the axial plane was 0.25, while T-MRI-NWI2, measured on the coronal plane at the patellar tendon groove level, was 0.23. These findings differ slightly from previous studies (Al-Saeed et al., 2012; Bayer et al., 2020; Domzalski et al., 2010; Shaw et al., 2015), likely due to variations in the demographic characteristics of the study population, measurement methods, imaging planes and definitions of reference values. When analyzing the relationship between intercondylar notch morphology and ACL injuries, Hoteya et al. measured the NWI at the posterior cruciate ligament insertion point (NWIP) using MRI and suggested that this method effectively reflects notch narrowing. Using ROC curve analysis, they established critical values for NWIA and NWIP as 0.25 (Hoteya et al., 2011).

In this study, MRI-NWI3 at the posterior cruciate ligament level demonstrated a significant gender difference, with the NWI for the female group (F-MRI-NWI3) being 0.27 and for the male group (M-MRI-NWI3) being 0.26. These values are higher than those reported by Hoteya et al., which may be attributed to differences in the calculation method for cutoff points or variations in the study population (Hoteya et al., 2011).

4.2 Notch Shape Index (NSI)

Study has classified intercondylar notches into A-type, U-type, and W-type categories (van Eck et al., 2010). While this classification provides a theoretical framework for related research, it also has certain limitations. Firstly, this approach may oversimplify the complex, continuous variations in intercondylar notch morphology among individuals. Additionally, it relies on subjective judgment by observers, which could lead to inconsistencies in classification results. Therefore, in this study, a method based on the consistency ratio, calculating the NSI at the same level to quantitatively evaluate intercondylar notch morphology was adopted.

In research investigating Cyclops syndrome following ACL reconstruction, the NSI has been recognized as an important parameter for assessing the potential risk of conflict between the intercondylar notch and the graft (Ficek et al., 2021). While the traditional NWI is commonly used to evaluate the degree of notch narrowing, some researchers have suggested combining NWI and NSI, along with MRI, for a more precise quantitative analysis of notch morphology.

This combined approach provides a more comprehensive understanding of the relationship between intercondylar notch morphology and Cyclops syndrome. Although NSI shows promise in reducing the incidence of this syndrome, its clinical applicability requires further validation through larger-scale studies (Ficek et al., 2021).

In a study by Lazar Stijak et al., morphological parameters of the intercondylar notch, particularly the NSI, were analyzed to evaluate their association with ACL rupture. The study included 99 participants, divided into an ACL rupture group and a control group, with NSI measured via axial knee MRI scans (Stijak et al., 2012).

The results showed that NSI values in the ACL rupture group were significantly lower than those in the control group (0.685 ± 0.089 vs. 0.720 ± 0.096), with this difference being especially pronounced in male participants. The study concluded that a lower NSI value is associated with an increased risk of ACL rupture, particularly in males (Stijak et al., 2012).

In the study by Mark D. Tillman et al., the authors investigated gender differences in the geometry of the intercondylar notch using cadaveric samples, with a particular focus on the NSI. The results showed that NSI values on the coronal plane were significantly higher in males compared to females. The authors hypothesized that this difference in intercondylar notch geometry might be one of the key factors contributing to the higher incidence of ACL injuries in females (Tillman et al., 2002). However, the findings of the present study differ from those of Tillman et al., as no statistically significant gender differences in NSI values were observed. In this study, the reference NSI values for the overall group were 0.54 for axial NSI (T-MRI-NSI1) and 0.58 for coronal NSI (T-MRI-NSI2).

These differences may be attributed to multiple factors. Firstly, sample selection and sample size could influence study results, as an insufficient sample size or selection bias may fail to accurately represent the overall population. Secondly, the precision of MRI scans, which directly impacts the accuracy of NSI measurements, is affected by various factors, including resolution, signal-to-noise ratio (SNR), magnetic field strength, coil selection, and specific measurement methodologies. Additionally, genetic variations play a role in ACL injury susceptibility. For example, polymorphisms in the COL5A1 gene, such as rs12722, may impair the synthesis and structure of type V collagen, leading to disorganized collagen fiber arrangement and reduced ligament tensile strength. This effect can be amplified by interactions with estrogen signaling, increasing ligament fragility during hormonal fluctuations. Moreover, polymorphisms in other genes, such as MMP3 and ESR1, may further influence susceptibility by regulating collagen metabolism balance and hormonal responses (Posthumus et al., 2009). These genetic differences, combined with sex-related biological characteristics or hormonal cycles, age, ethnic background and study design factors (such as sample size, statistical methods and data distribution), collectively contribute to individual biomechanical variations. These variations may make certain populations more prone to ACL ruptures during physical activity. However, drawing definitive conclusions requires a comprehensive evaluation that considers study limitations and consistency with previous findings.

Therefore, despite some differences in research findings, these studies provide preliminary scientific evidence for understanding NSI and its potential variability between genders. Future research should focus on larger sample sizes and multicenter study designs, utilizing standardized measurement and analysis methods to further validate the clinical value and applicability of NSI.

4.3 Notch Volume (CSA)

Some studies have explored the relationship between femoral intercondylar notch volume and ACL injuries, particularly differences in notch volume between participants with and without ACL injuries. A meta-analysis of these studies indicated that a smaller intercondylar notch volume might increase the risk of ACL injuries. This finding supports the hypothesis that intercondylar notch volume could be a potential risk factor for ACL injuries while also emphasizing the importance of considering notch morphology in imaging evaluations (Jha et al., 2022).

In this study, intercondylar notch volume was represented by the measurement of CSA. The results showed that CSA values were generally lower in females than in males in both the axial and coronal planes. This finding aligns with previous studies. This gender difference may be attributed to several factors. Firstly, significant differences in skeletal structure and physiological characteristics exist between males and females, with male bones typically being larger and denser. Secondly, estrogen levels in females significantly influence bone shape and density, potentially resulting in smaller intercondylar notch volumes. Additionally, males are more likely to engage in high-intensity physical activities, which increase mechanical loads on the skeleton and may further promote the expansion and reinforcement of the intercondylar notch. Furthermore, variations in growth and development patterns, as well as the effects of sex and growth hormones, may also contribute to differences in notch morphology (Swami et al., 2013; van Eck et al., 2010).

These findings support the perspective that intercondylar notch volume and its relationship with scanning direction exhibit gender differences. They provide new insights into the influence of gender on the anatomical structure of the knee joint and further enhance our understanding of its potential clinical significance.

4.4 Clinical Significance of Intercondylar Notch Morphology Measurements

Multiple studies have confirmed that a narrow intercondylar notch is a significant independent risk factor for ACL injuries (Al-Saeed et al., 2012; Çimen, 2022; Çimen et al., 2023; Hoteya et al., 2011). These investigations have employed various methods, including anatomical analysis of participant cadaveric bones, studies on knee joint geometry and MRI morphological assessments augmented by deep learning models. The findings consistently demonstrate a strong correlation between notch width and shape and the occurrence of ACL injuries, with notch narrowing significantly increasing the likelihood of ACL rupture. This conclusion has been further validated through precise measurements in anatomical studies and automated segmentation models.

The results of these studies emphasize that intercondylar notch morphology is a critical reference index for predicting and preventing ACL injuries (Çimen, 2022; Çimen et al., 2023; Everhart et al., 2012; Hasoon & Al-Dadah, 2023; Li et al., 2022; Maheshwari et al., 2023). Evidence-based medical research, supported by multiple meta-analyses, has reinforced this risk factor. These comprehensive analyses, integrating data from various studies, have unequivocally identified a significant association between notch dimensions, particularly narrowing and ACL injury occurrence. A narrow notch dramatically elevates the risk of ACL rupture, a finding widely supported by empirical evidence. This solidifies intercondylar notch morphology as a key anatomical indicator for predicting and preventing ACL injuries (Li et al., 2018; Li et al., 2020; Zeng et al., 2012).

Numerous studies have examined the mechanisms by which intercondylar notch narrowing contributes to ACL injuries. For instance, studies by Al-Saeed et al. and Li Z et al. suggest that a narrowed notch restricts the functional space of the ACL, leading to increased mechanical compression and stress concentration during knee joint movements, thereby elevating the risk of injury (Al-Saeed et al., 2012; Li et al., 2020). Additionally, high-resolution MRI studies have revealed that a narrow notch is often associated with a smaller ACL, which may make the ligament more susceptible to damage during high-intensity activities (Dienst et al., 2006). Narrow notches also alter the stress distribution experienced by the ACL, further increasing the likelihood of injury (Bayer et al., 2020). Studies examining the relationship between three-dimensional notch volume and ACL injuries have demonstrated that a smaller notch volume significantly raises the probability of ACL rupture (Al-Saeed et al., 2012; Li et al., 2020). Furthermore, it has been observed that notch narrowing is strongly associated not only with unilateral ACL injuries but also with bilateral ACL injuries (Hoteya et al., 2011). In summary, these studies indicate that notch narrowing significantly increases the risk of ACL injury through various mechanisms, highlighting its critical role in understanding and addressing ligament damage.

Moreover, femoral notch narrowing and increased tibial slope have been widely recognized as potential risk factors for ACL injuries (Bayer et al., 2020; Shen et al., 2019). Detailed analyses of femoral and tibial anatomical structures in healthy individuals, using imaging techniques such as MRI and CT, have revealed that these features are prevalent in over half of the population (Micicoi et al., 2021). Given this, precise preoperative anatomical evaluation becomes particularly critical in determining whether to perform notchplasty during ACL reconstruction surgery. This study also emphasizes the importance of considering individual skeletal structural characteristics alongside external risk factors associated with sports activities. The high prevalence of these risk factors in the general population underscores the necessity of adopting preventive measures tailored to individual anatomical features. Such strategies can more effectively identify and mitigate the potential risk of ACL injuries. In conclusion, these research findings provide significant theoretical support for understanding the mechanisms underlying ACL injuries and lay a solid foundation for developing personalized prevention strategies.

5. Conclusion

This study highlights significant gender differences in femoral intercondylar notch anatomy, particularly in the posterior cruciate ligament tibial attachment notch width index and intercondylar notch cross-sectional area, emphasizing the influence of gender on knee joint structure. These findings underscore the importance of individualized assessments for ACL injury prevention, considering both external risk factors, such as physical activity and internal anatomical variations to develop tailored prevention strategies. Additionally, preoperative evaluations play a pivotal role in ACL reconstruction surgery by informing decisions regarding notchplasty and optimizing personalized treatment plans. A comprehensive understanding of knee anatomy and injury mechanisms provides a robust foundation for improved prevention and surgical outcomes.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The study was approved by the Research Management Centre, MAHSA University (RMC/JUN/2024/EC05) and the ethics committee of Baise People’s Hospital (approval number: KY2024053001).

HUMAN AND ANIMAL RIGHTS

Not applicable.

CONSENT FOR PUBLICATION

Not applicable.

DECLARATION OF AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

The English language of the article was improved with ChatGPT. Upon generating draft language, the author reviewed, edited and revised the language to their own liking and takes ultimate responsibility for the content of this publication.

AVAILABILITY OF DATA AND MATERIALS

The datasets supporting the conclusions of this article are available from the corresponding author on reasonable request.

FUNDING

None

CONFLICT OF INTEREST

The authors declare that none of them has any conflict of interest.

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REFERENCES

[1] Agrawal, A. C., Rakshit, J., Sakale, H., Kar, B., & Raj, M. (2021). Anatomical considerations of intercondylar notch dimensions of femur in cadavers with intact anterior cruciate ligament. *Journal of Orthopedics, Traumatology and Rehabilitation*, *13*(1), 38-40. https://doi.org/10.4103/jotr.jotr_27_21

[2] Akgün, A. S. (2020). Evaluation of anterior cruciate ligament injury and intercondylar notch stenosis in patients with knee osteoarthritis with MRI. *Van Medical Journal*, *27*(1), 10-16. https://doi.org/10.5505/vtd.2020.58265

[3] Al-Saeed, O., Brown, M., Athyal, R., & Sheikh, M. (2012). Association of femoral intercondylar notch morphology, width index and the risk of anterior cruciate ligament injury. *Knee Surgery, Sports Traumatology, Arthroscopy*, *21*(3), 678-682. https://doi.org/10.1007/s00167-012-2038-y

[4] Albano, D., Viglino, U., Esposito, F., Rizzo, A., Messina, C., Gitto, S., Fusco, S., Serpi, F., Kamp, B., Müller-Lutz, A., D'Ambrosi, R., Sconfienza, L. M., & Sewerin, P. (2024). Quantitative and compositional MRI of the articular cartilage: A narrative review. *Tomography* *10*(7), 949-969. https://doi.org/10.3390/tomography10070072

[5] Bayer, S., Meredith, S. J., Wilson, K. W., de Sa, D., Pauyo, T., Byrne, K., McDonough, C. M., & Musahl, V. (2020). Knee morphological risk factors for anterior cruciate ligament injury: A systematic review. *Journal of Bone and Joint Surgery*, *102*(8), 703-718. https://doi.org/10.2106/jbjs.19.00535

[6] Chen, C., Ma, Y., Geng, B., Tan, X., Zhang, B., Jayswal, C. K., Khan, M. S., Meng, H., Ding, N., Jiang, J., Wu, M., Wang, J., & Xia, Y. (2016). Intercondylar notch stenosis of knee osteoarthritis and relationship between stenosis and osteoarthritis complicated with anterior cruciate ligament injury: A study in MRI. *Medicine*, *95*(17), e3439-e3439. https://doi.org/10.1097/MD.0000000000003439

[7] Chen, S., Zheng, Z., Guo, J., Hong, S., Zhou, W., Xie, J., & Wang, W. (2023). Three-dimensional computed tomography mapping techniques in the morphometric analysis of AO/OTA 33A and 33C distal femoral fractures: A retrospective single-center study. *Frontiers in bioengineering and biotechnology*, *11*, 1162214-1162214. https://doi.org/10.3389/fbioe.2023.1162214

[8] Çimen, K. (2022). Evaluation of the anterior cruciate ligament related distal femur and proximal tibia anatomical structures on dry adult bones. *Revista Argentina de Anatomía Clínica*, *14*(3), 99-106. https://doi.org/10.31051/1852.8023.v14.n3.38892

[9] Çimen, K., Otağ, İ., & Oztemür, Z. (2023). The relationship of distal femur and proximal tibia morphology with anterior cruciate ligament injuries. *Surgical and Radiologic Anatomy*, *45*(4), 495-501. https://doi.org/10.1007/s00276-023-03097-9

[10] Dienst, M., Schneider, G., Altmeyer, K., Voelkering, K., Georg, T., Kramann, B., & Kohn, D. (2006). Correlation of intercondylar notch cross sections to the ACL size: A high resolution MR tomographic in vivo analysis. *Archives of Orthopaedic and Trauma Surgery*, *127*(4), 253-260. https://doi.org/10.1007/s00402-006-0177-7

[11] Domzalski, M., Grzelak, P., & Gabos, P. (2010). Risk factors for anterior cruciate ligament injury in skeletally immature patients: Analysis of intercondylar notch width using magnetic resonance imaging. *International orthopaedics*, *34*(5), 703-707. https://doi.org/10.1007/s00264-010-0987-7

[12] Dwivedi, A. K., Airan, N., & Bhatnagar, R. (2022). A cross-sectional observational study on distal femoral morphometry in West-central Maharashtra, India. *JOURNAL OF CLINICAL AND DIAGNOSTIC RESEARCH*. https://doi.org/10.7860/jcdr/2022/59749.17006

[13] Everhart, J. S., Flanigan, D. C., & Chaudhari, A. M. W. (2012). Anteromedial ridging of the femoral intercondylar notch: An anatomic study of 170 archival skeletal specimens. *Knee Surgery, Sports*

Traumatology, Arthroscopy, *22*(1), 80-87. https://doi.org/10.1007/s00167-012-2282-1

[14] Ficek, K., Rajca, J., Cholewiński, J., Racut, A., Gwiazdoń, P., Przednowek, K., & Hajduk, G. (2021). Analysis of intercondylar notch size and shape in patients with cyclops syndrome after anterior cruciate ligament reconstruction. *Journal of orthopaedic surgery and research*, *16*(1), 554-554. https://doi.org/10.1186/s13018-021-02706-w

[15] Hasoon, J., & Al-Dadah, O. (2023). Knee anatomic geometry accurately predicts risk of anterior cruciate ligament rupture. *Acta Radiologica* *64*(5), 1904-1911. https://doi.org/10.1177/02841851231152329

[16] Hirtler, L., Kainberger, F., & Röhrich, S. (2022). The intercondylar fossa-A narrative review. *Clinical Anatomy* *35*(1), 2-14. https://doi.org/10.1002/ca.23773

[17] Hoteya, K., Kato, Y., Motojima, S., Ingham, S. J., Horaguchi, T., Saito, A., & Tokuhashi, Y. (2011). Association between intercondylar notch narrowing and bilateral anterior cruciate ligament injuries in athletes. *Archives of Orthopaedic and Trauma Surgery*, *131*(3), 371-376. https://doi.org/10.1007/s00402-010-1254-5

[18] Jha, V., Azam, M. Q., Jain, P., & Bali, S. A. (2022). Does femoral intercondylar notch volume differ in anterior cruciate ligament-injured adult patients compared to the uninjured?: A meta-analysis. *Clinics in orthopedic surgery*, *14*(1), 76-89. https://doi.org/10.4055/cios20163

[19] Kayani, B., Konan, S., Ahmed, S. S., Chang, J. S., Ayuob, A., & Haddad, F. S. (2020). The effect of anterior cruciate ligament resection on knee biomechanics. *The Bone & Joint Journal*, *102-B*(4), 442-448. https://doi.org/10.1302/0301-620x.102b4.bjj-2019-1238.r2

[20] Keremu, A., Mijiti, N., Mijiti, S., Tuxun, A., & Abudurexiti, A. (2020). Evaluation of the application value of a three-dimensional digital model of the knee in clinical practice. *The Journal of international medical research*, *48*(5), 300060519889742-300060519889742. https://doi.org/10.1177/0300060519889742

[21] Korolev, A. V., Afanasyev, A. P., Il'in, D. O., Gerasimov, D. O., Ryazantsev, M. S., Kadantsev, P. M., & Zaripov, A. R. (2020). Damage of the knee posterior cruciate ligament: biomechanics, basic diagnostics, treatment and secondary osteoarthritis prevention directions. *Pirogov Russian Journal of Surgery*(9), 130. https://doi.org/10.17116/hirurgia2020091130

[22] Lam, M.-H., Fong, D. T., Yung, P. S., Ho, E. P., Chan, W.-Y., & Chan, K.-M. (2009). Knee stability assessment on anterior cruciate ligament injury: Clinical and biomechanical approaches. *BMC Sports Science, Medicine and Rehabilitation*, *1*(1), 20-20. https://doi.org/10.1186/1758-2555-1-20

[23] Li, H., Zeng, C., Wang, Y., Wei, J., Yang, T., Cui, Y., Xie, D., Liu, H., & Lei, G.-h. (2018). Association between magnetic resonance imaging–measured intercondylar notch dimensions and anterior cruciate ligament injury: A meta-analysis. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, *34*(3), 889-900. https://doi.org/10.1016/j.arthro.2017.08.299

[24] Li, M., Bai, H., Zhang, F., Zhou, Y., Lin, Q., Zhou, Q., Feng, Q., & Zhang, L. (2022). Automatic segmentation model of intercondylar fossa based on deep learning: A novel and effective assessment method for the notch volume. *BMC musculoskeletal disorders*, *23*(1), 426-426. https://doi.org/10.1186/s12891-022-05378-7

[25] Li, X., Kim, J., Yang, M., Ok, A. H., Zbýň, Š., Link, T. M., Majumdar, S., Ma, C. B., Spindler, K. P., & Winalski, C. S. (2024). Cartilage compositional MRI-a narrative

review of technical development and clinical applications over the past three decades. *Skeletal radiology*, *53*(9), 1761-1781. https://doi.org/10.1007/s00256-024-04734-z

[26] Li, Z., Li, C., Li, L., & Wang, P. (2020). Correlation between notch width index assessed via magnetic resonance imaging and risk of anterior cruciate ligament injury: An updated meta-analysis. *Surgical and Radiologic Anatomy*, *42*(10), 1209-1217. https://doi.org/10.1007/s00276-020-02496-6

[27] Maheshwari, S. G., Kuber, R., Lamghare, P., Thomas, J., Arkar, R., Avhad, M., Tharmalingam, T., Bhamare, D. S., Katuri, S., Nagraj, H., Redla, S., Elsayad, M., & Vrizidou, S. (2023). Anterior cruciate ligament (ACL) injury: Correlation with MRI morphometry. *Egyptian Journal of Radiology and Nuclear Medicine*, *54*(1). https://doi.org/10.1186/s43055-023-01073-2

[28] Micicoi, G., Jacquet, C., Khakha, R., LiArno, S., Faizan, A., Seil, R., Kocaoglu, B., Cerciello, S., Martz, P., & Ollivier, M. (2021). Femoral and tibial bony risk factors for anterior cruciate ligament injuries are present in more than 50% of healthy individuals. *The American Journal of Sports Medicine*, *49*(14), 3816-3824. https://doi.org/10.1177/03635465211050421

[29] Nacey, N. C., Geeslin, M. G., Miller, G. W., & Pierce, J. L. (2017). Magnetic resonance imaging of the knee: An overview and update of conventional and state of the art imaging. *Journal of Magnetic Resonance Imaging*, *45*(5), 1257-1275. https://doi.org/10.1002/jmri.25620

[30] Oshima, T., Putnis, S., Grasso, S., & Parker, D. A. (2020). The space available for the anterior cruciate ligament in the intercondylar notch is less in patients with ACL injury. *Knee Surgery, Sports Traumatology, Arthroscopy*, *28*(7), 2105-2115. https://doi.org/10.1007/s00167-020-05921-w

[31] Phombut, C., Rooppakhun, S., & Sindhupakorn, B. (2021). Morphometric analysis and three-dimensional computed tomography reconstruction of Thai distal femur. *Applied Sciences*, *11*(3), 1052. https://doi.org/10.3390/app11031052

[32] Posthumus, M., September, A. V., O'Cuinneagain, D., van der Merwe, W., Schwellnus, M. P., & Collins, M. (2009). The COL5A1 gene is associated with increased risk of anterior cruciate ligament ruptures in female participants. *The American Journal of Sports Medicine*, *37*(11), 2234-2240. https://doi.org/10.1177/0363546509338266

[33] S, A. N. (2021). An osteological study of distal end of femur in adult South Indian population. *Medpulse International Journal of Anatomy*, *19*(1), 10-12. https://doi.org/10.26611/10011913

[34] Shaw, K. A., Dunoski, B., Mardis, N., & Pacicca, D. (2015). Knee morphometric risk factors for acute anterior cruciate ligament injury in skeletally immature patients. *Journal of children's orthopaedics*, *9*(2), 161-168. https://doi.org/10.1007/s11832-015-0652-1

[35] Shen, X., Xiao, J., Yang, Y., Liu, T., Chen, S., Gao, Z., & Zuo, J. (2019). Multivariable analysis of anatomic risk factors for anterior cruciate ligament injury in active individuals. *Archives of Orthopaedic and Trauma Surgery*, *139*(9), 1277-1285. https://doi.org/10.1007/s00402-019-03210-x

[36] Stein, V., Li, L., Guermazi, A., Zhang, Y., Kent Kwoh, C., Eaton, C. B., Hunter, D. J., & Investigators, O. A. I. (2010). The relation of femoral notch stenosis to ACL tears in persons with knee osteoarthritis. *Osteoarthritis and cartilage*, *18*(2), 192-199. https://doi.org/10.1016/j.joca.2009.09.006

[37] Stijak, L., Malis, M., Maksimovic, R.,

Aksic, M., & Filipovic, B. (2012). The influence of the morphometric parameters of the intercondylar notch on rupture of the anterior cruciate ligament. *Vojnosanitetski pregled*, *69*(7), 576-580. https://doi.org/10.2298/vsp101224012s

[38] Swami, V. G., Mabee, M., Hui, C., & Jaremko, J. L. (2013). Three-dimensional intercondylar notch volumes in a skeletally immature pediatric population: A magnetic resonance imaging–based anatomic comparison of knees with torn and intact anterior cruciate ligaments. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, *29*(12), 1954-1962. https://doi.org/10.1016/j.arthro.2013.08.031

[39] Tillman, M. D., Smith, K. R., Bauer, J. A., Cauraugh, J. H., Falsetti, A. B., & Pattishall, J. L. (2002). Differences in three intercondylar notch geometry indices between males and females: A cadaver study. *The Knee*, *9*(1), 41-46. https://doi.org/10.1016/s0968-0160(01)00135-1

[40] van Eck, C. F., Martins, C. A. Q., Vyas, S. M., Celentano, U., van Dijk, C. N., & Fu, F. H. (2010). Femoral intercondylar notch shape and dimensions in ACL-injured patients. *Knee Surgery, Sports Traumatology, Arthroscopy*, *18*(9), 1257-1262. https://doi.org/10.1007/s00167-010-1135-z

[41] Xu, P., Li, Y.-l., Chen, W.-d., Yang, G., Wang, G.-l., Tong, L., & Hu, M. (2011). The anatomy research on three-dimensional digital intercondylar notch model based on MRI images: Comparison of three-dimensional data and measurement data. *Chinese Journal of Tissue Engineering Research*, *15*(43), 8006.

[42] Zeng, C., Gao, S.-g., Wei, J., Yang, T.-b., Cheng, L., Luo, W., Tu, M., Xie, Q., Hu, Z., Liu, P.-f., Li, H., Yang, T., Zhou, B., & Lei, G.-h. (2012). The influence of the intercondylar notch dimensions on injury of the anterior cruciate ligament: A meta-analysis. *Knee Surgery, Sports Traumatology, Arthroscopy*, *21*(4), 804-815. https://doi.org/10.1007/s00167-012-2166-4