Femoral and Tibial Bony Risk Factors for Anterior Cruciate Ligament Injuries Are Present in More Than 50% of Healthy Individuals.

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Grégoire Micicoi,[*†] Christophe Jacquet,[†] Raghbir Khakha,[‡] Sally LiArno,[§] Ahmad Faizan,[§] Romain Seil,[||] MD, Baris Kocaoglu,[¶] MD, Simone Cerciello,[#**] Pierre Martz,[†] and Matthieu Ollivier,[†††] MD, PhD

Background: Anterior cruciate ligament (ACL) injuries are multifactorial events that may be influenced by morphometric parameters. Associations between primary ACL injuries or graft ruptures and both femoral and tibial bony risk factors have been well described in the literature.

Purpose: To determine values of femoral and tibial bony morphology that have been associated with ACL injuries in a reference population. Further, to define interindividual variations according to participant demographics and to identify the proportion of participants presenting at least 1 morphological ACL injury risk factor.

Study Design: Cross-sectional study; Level of evidence, 3.

Methods: Computed tomography scans of 382 healthy participants were examined. The following bony ACL risk factors were analyzed: notch width index (NWI), lateral femoral condylar index (LFCI), medial posterior plateau tibial angle (MPPTA), and lateral posterior plateau tibial angle (LPPTA). The proportion of this healthy population presenting with at least 1 pathological ACL injury risk factor was determined. A multivariable logistic regression model was constructed to determine the influence of demographic characteristics.

Results: According to published thresholds for ACL bony risk factors, 12% of the examined knees exhibited an intercondylar notch width <18.9 mm, 25% had NWI <0.292, 62% exhibited LFCI <0.67, 54% had MPPTA <83.6°, and 15% had LPPTA <81.6°. Only 14.4% of participants exhibited no ACL bony risk factors, whereas 84.5% had between 2 and 4 bony risk factors and 1.1% had all bony risk factors. The multivariate analysis demonstrated that only the intercondylar notch width ($P < .0001$) was an independent predictor according to both sex and ethnicity; the LFCI ($P = .012$) and MMPTA ($P = .02$) were independent predictors according to ethnicity.

Conclusion: The precise definition of bony anatomic risk factors for ACL injury remains unclear. Based on published thresholds, 15% to 62% of this reference population would have been considered as being at risk. Large cohort analyses are required to confirm the validity of previously described morphological risk factors and to define which participants may be at risk of primary ACL injury and reinjury after surgical reconstruction.

Keywords: intercondylar notch width (NWI); lateral femoral condylar index (LFCI); posterior tibial slope; ACL rupture; morphological risk factors

Reported risk factors for anterior cruciate ligament (ACL) injury include anatomic, hormonal, and neuromuscular parameters and bony morphological features including femoral condylar depth, lateral femoral notch, tibial plateau slope, and intercondylar notch shape.[3,7,12,21,24,33]

Pedoia et al[23] suggested that variations of the femoral intercondylar width, including narrow femoral notch volume, which is associated with a higher incidence of ACL injuries, may predispose individuals to ACL injuries.[15,37,38] More recently, a spherical appearance of the lateral femoral condyle or an excessive posterior femoral condylar offset has been implicated in an increased risk of ACL injury.[13,24] An increased posterior tibial slope appears to predispose to primary ACL rupture[2,9,14] or failure after ACL reconstruction,[10,19,36] with the lateral plateau having a more pivotal role compared with the medial plateau.[4,13]

TABLE 1
Abbreviations Used

Abbreviation	Definition
ACL	Anterior cruciate ligament
AD	Absolute difference
BMI	Body mass index
CT	Computed tomography
INW	Intercondylar notch width
LCECR	Lateral condylar extension circle radius
LCFCR	Lateral condylar flexion circle radius
LFCI	Lateral femoral condylar index
LPPTA	Lateral posterior plateau tibial angle
MPPTA	Medial posterior plateau tibial angle
MRI	Magnetic resonance imaging
NWI	Notch width index
ΔPPTA	Difference between LPPTA and MPPTA

Identification of these bony factors may represent an important step in the development of prevention strategies for ACL injuries.[16]

Most studies have focused on ACL bony morphological risk factors in patients with ACL ruptures or reruptures, but none have assessed the rates of participants estimated to be at risk for ACL injury in a healthy population.

The primary aim of the present study was to establish normal values of femoral and tibial bony parameters that are generally associated with ACL tears. Second, the rates of participants considered to be at risk according to the published thresholds reported in the literature were assessed. Third, interindividual variations of these bony values according to demographic characteristics were analyzed. It was hypothesized that a large proportion of healthy participants would exceed critical reported thresholds considered to pose a risk of ACL injury. Abbreviations used in this article are defined in Table 1.

METHODS

A computed tomography (CT) scan–based modeling and analysis system on >15,000 bone segments was used for this study (Stryker Orthopaedic Modeling and Analytics [SOMA]; Stryker).[25] The SOMA database consists of >25,000 bone models obtained from >3600 participants worldwide. All scans were obtained as per local legal and regulatory requirements, which included ethical board approval and informed patient consent, where appropriate. CT scans were acquired exclusively for medical indications such as polytrauma (20%), CT angiography (70%), and other reasons (ie, total joint arthroplasty) (10%). A total of 382 participants (184 men and 198 women; mean age, 59.6 ± 15.9 years; mean body mass index [BMI], 24.7 ± 4.7) had reliable and complete data imaging sets that were selected and included (Table 2).

TABLE 2
Demographic and Anatomic Parameters Evaluated in Our Global Series[a]

	Mean ± SD	Range (Min-Max)
Demographic parameters		
Age, y	59.6 ± 15.9	18-92
Height, kg	164.1 ± 8.6	140-189
Weight, cm	67.2 ± 15.9	39-110
Body mass index	24.7 ± 4.7	15.6-41.6
Anatomic parameters		
Intercondylar notch width, mm	22.0 ± 2.6	15.6-29.1
Medial condylar width, mm	25.0 ± 2.2	19.8-31.1
Lateral condylar width, mm	24.0 ± 2.2	18.2-29.8
NWI	0.305 ± 0.022	0.200-0.400
LCFCR	20.3 ± 1.8	16.4-26.3
LCECR	31.1 ± 3.3	21.4-40.1
LFCI	0.65 ± 0.15	0.50-0.96
MPPTA, deg	83.3 ± 3.7	72.8-94.1
LPPTA, deg	84.7 ± 3.3	74.3-92.8
ΔPPTA	3.50 ± 2.59	0.1-13.1

[a]LCECR, lateral condylar extension circle radius; LCFCR, lateral condylar flexion circle radius; LFCI, lateral femoral condylar index; LPPTA, lateral posterior plateau tibial angle; MPPTA, medial posterior plateau tibial angle; NWI, notch width index; ΔPPTA, difference between LPPTA and MPPTA.

The study sample consisted of participants from different ethnic backgrounds (196 White and 186 Asian participants). The anatomic patterns of the pelvis, bilateral femur, bilateral tibia, and patella were examined. The healthy population consisted of participants without bone or joint abnormalities including no substantial osteoarthritis (Ahlbäck grade ≤I, without osteophytes) or evidence of previous surgery, including ACL reconstruction. CT scans were performed in different institutions worldwide and were included in the study only if the thickness of the slices was <1.5 mm and no motion artifacts were present. These measurements were then profiled to each bone on the

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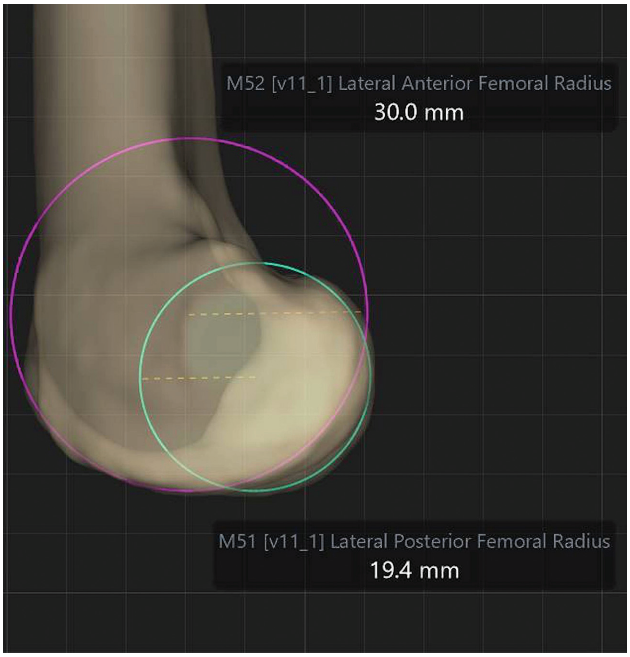

Figure 1. The lateral femoral condyle index corresponds to the diameter of the flexion circle divided by the diameter of the extension circle, allowing an estimate of the sphericity of the lateral femoral condyle.

database by the automated software. The measurements resulted in reproducible and consistent parameters for each participant with an associated margin of error of <2 mm and <1°.[1,26]

The medial condylar width, lateral condylar width, intercondylar notch width, notch width index (NWI), lateral condylar flexion circle radius (LCFCR), lateral condylar extension circle radius (LCECR), lateral femoral condylar index (LFCI), medial posterior plateau tibial angle (MPPTA), lateral posterior plateau tibial angle (LPPTA), and difference between LPPTA and MPPTA (ΔPPTA) were assessed for each knee. The values were then profiled relative to the database within a margin of error <2 mm and 1°.[1,26] Medial and lateral condylar widths were measured on the widest part of the distal femur. The width of the intercondylar notch was measured at the level of the axial slice where both condyles showed their largest width. NWI was defined as the ratio between the width of the intercondylar notch and the width of the distal femur. The LCFCR and LCECR were determined by the flexion and extension curvature of the lateral femoral condyle approximated by 2 circles. Radii of these circles were then measured. To estimate the sphericity of the lateral femoral condyle, the LFCI was then determined. The LFCI was calculated according to the method described by Hodel et al,[13] dividing the radius of the flexion circumference by the radius of the extension circumference (Figure 1).

The proximal tibial plane was calibrated by marking >35 points on the medial and lateral tibial compartments. The mechanical axis of the tibia was defined as the line connecting the center of the tibial spine and the center of the ankle joint. The MPPTA and LPPTA were measured as the angles subtended between the medial and lateral tibial plateaus, respectively, and the mechanical axis of the tibia in the sagittal plane (Figure 2).

To perform this study, we explored an anonymized database after obtaining local ethical committee approval of the research protocol (Aix-Marseille University, No. 2019-127).

Thresholds for ''Abnormal'' Morphometric Parameters

A literature search was performed on Medline. A preliminary screening of the articles was based on title and abstract analysis. A second screening was based on a full-text review. Cadaveric studies were excluded from the analysis. For relevant studies, the associations between ACL injury and femoral or tibial bony morphological factors were investigated. Established anatomic thresholds were searched in the ACL injury group. Values that were considered as "at risk" were intercondylar notch width <20.2 mm,[17,38] NWI <0.292,[15,17,33,38] LFCI <0.67,[13] MPPTA <83.6°,[11] and LPPTA <81.6°[4,10,11,13] (Table 3). According to these thresholds, we aimed to define the percentage of healthy participants who could be considered to be at a higher risk of ACL injury.

Some bony factors have not been evaluated by CT scan–based modeling, such as the lateral femoral condylar ratio,[24] the notch shape,[7] and the bony morphology of the femoral lateral condyle.[8]

Statistical Analysis

Mean values and standard deviations were determined for each of the measured anatomic parameters. Normal (Gaussian) distributions were defined. Univariate analysis was performed using *t* tests to estimate differences between groups. Multiple linear regression models were developed to establish the determinants for each of the variables. For each model, variables with a *P* value <.1 were kept in the final model.

Sample size was calculated based on the estimated intercondylar notch width (notch width = 21.65 ± 2.70 mm[38]). For a required level of statistical significance of $\alpha = .05$ and a power of $1 - \beta = 0.9$, 50 lower limb pairs would be required in each group or subgroup to detect >2-mm difference between groups and subgroups. A trained statistician (M.O.) performed statistical analysis using SPSS software (Version 22; SPSS Inc). All calculations were based on 2-tailed tests.

RESULTS

Mean values, dispersion, and range of morphometric parameters are reported in Table 2. Regarding the previously published thresholds (Figure 3), 25% of the healthy population had an intercondylar notch width <20.2 mm, 25% had NWI <0.292, 62% had LFCI <0.67, 54% had MPPTA <83.6°, and 15%-49% had LPPTA <81.6°-85.0° and therefore met the definition of being considered at risk for ACL injury (Table 3). Only 14.4% of participants

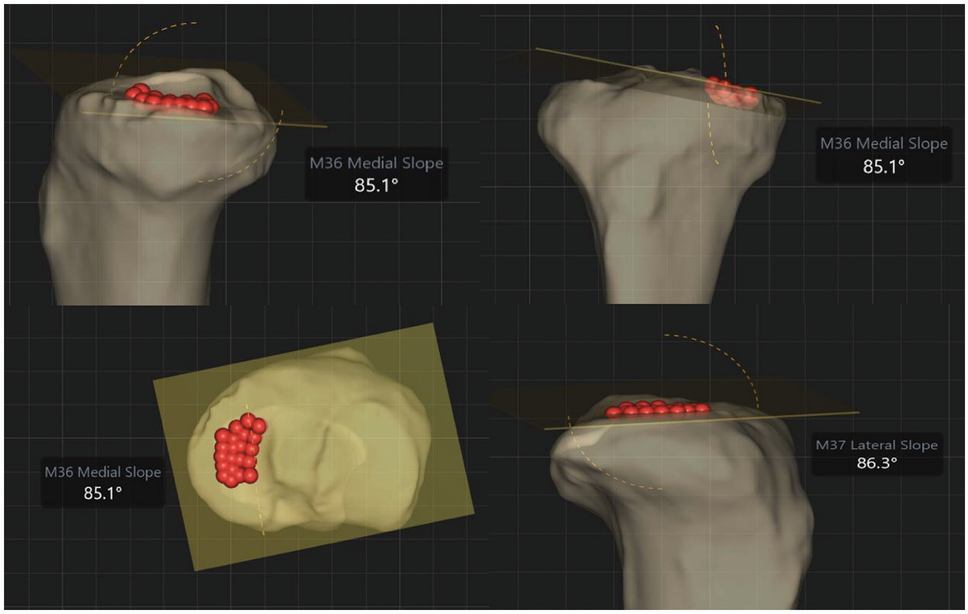

Figure 2. The lateral and medial proximal tibial planes are calibrated by marking >35 points on both compartments. The mechanical axis of the tibia is defined as the line connecting the center of the tibial spine and the center of the ankle joint. The medial posterior plateau tibial angle and lateral posterior plateau tibial angle were measured as the angles subtended between the medial and lateral tibial plateau, respectively, and the mechanical axis of the tibia in the sagittal plane.

TABLE 3
Comparison of Femoral and Tibial Risk Factors With the Published Data Sets[a]

				Bony Risk Factors Analyzed						
Lead Author (Year)	Imaging Technique	Sample Size	Population	Mean Intercondylar Notch Width	Mean NWI	Mean LFCI	Mean MPPTA	Mean LPPTA	Our Results	% of Participants at Risk in Our Population Based on This Threshold
Zhang[38] (2019)	MRI	N = 240 Injury, n = 120	ACL injury	20.2 mm	0.292	NA	NA	NA	Intercondylar notch = 22.0 mm; NWI = 0.305	Intercondylar notch: 25% <20.2 mm; NWI: 25% <0.292
Ireland[17] (2001)	Radiographs	N = 294 Injury, n = 108	ACL injury	18.9 mm	0.23	NA	NA	NA	Intercondylar notch = 22.0 mm; NWI = 0.305	Intercondylar notch: 12% <18.9 mm; NWI: 0.0% <0.23
Hoteya[15] (2011)	Radiographs	N = 75 Bilateral injury, n = 25	Bilateral ACL injury	NA	0.257	NA	NA	NA	NWI = 0.305	NWI: 0.5% <0.257
Souryal[33] (1988)	Radiographs	N = 1120 Bilateral injury, n = 45	Bilateral ACL injury	NA	0.196	NA	NA	NA	NWI = 0.305	NWI: 0.0% <0.196
Hodel[13] (2019)	MRI	N = 60 Injury, n = 20	ACL injury	NA	NS	0.67	NS	85.0°	LFCI = 0.65; LPPTA = 84.7°	LFCI: 62% <0.67; LPPTA: 49% <85.0°
Hashemi[11] (2010)	MRI	N = 104 Injury, n = 49	ACL injury	NA	NA	NA	83.6°	82.1°	MPPTA = 83.3°; LPPTA = 84.7°	MPPTA: 54% <83.6°; LPPTA: 19% <82.1°
Grassi[10] (2019)	MRI	N = 86 Injury, n = 43	Failed ACL reconstruction	NA	NS	NA	NA	82.6° (optimal cutoff value)	LPPTA = 84.7°	LPPTA: 23% <82.6°
Christensen[4] (2015)	MRI	N = 70 Injury, n = 35	Failed ACL reconstruction	NA	NA	NA	NA	81.6°	LPPTA = 84.7°	LPPTA: 15% <81.6°
Stijak[34] (2008)	MRI	N = 66 Injury, n = 33	ACL injury	NA	NA	NA	NS	82.5°	LPPTA = 84.7°	LPPTA: 23% <82.5°

[a]ACL, anterior cruciate ligament; LFCI, lateral femoral condylar index; LPPTA, lateral posterior plateau tibial angle; MPPTA, medial posterior plateau tibial angle; MRI, magnetic resonance imaging; NA, not assessed; NS, not significant; NWI, notch width index.

exhibited no ACL bony risk factors, whereas 84.5% had between 2 and 4 bony risk factors and 1.1% had all bony risk factors in this healthy population (Figure 4).

Regarding sex subgroups, significant differences between men and women were found for medial (absolute difference [AD] = 2.8 ± 0.17 mm; $P < .0001$) and lateral

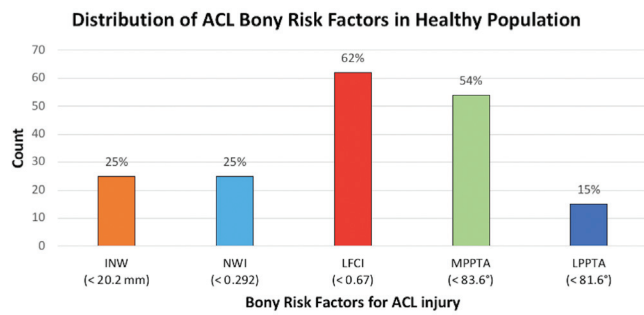

Figure 3. Distribution of bony risk factors for anterior cruciate ligament (ACL) injuries in a healthy population. INW, intercondylar notch width; LFCI, lateral femoral condylar index; LPPTA, lateral posterior plateau tibial angle; MPPTA, medial posterior plateau tibial angle; NWI, notch width index.

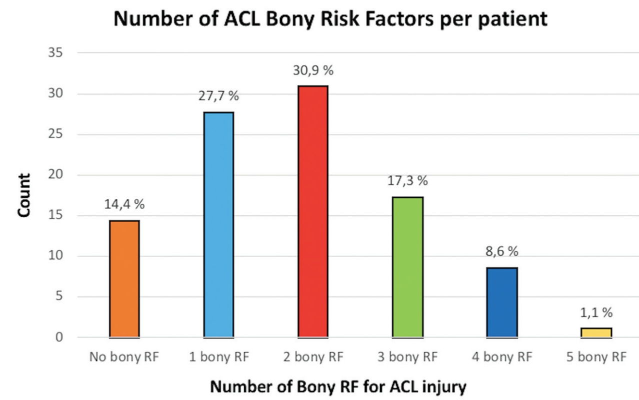

Figure 4. Number of anterior cruciate ligament (ACL) bony risk factors (RFs) per participant. Only 14.4% of the healthy population had no ACL bony risk factor according to the published thresholds; the threshold value of 81.6° was retained for the lateral posterior plateau tibial angle.

TABLE 4
Univariate Analysis Estimating Mean Distal Femoral Values and Absolute Differences Between Male and Female Participants[a]

	Men (n = 184)	Women (n = 198)	Absolute Difference	*P* Value
Intercondylar notch width, mm	23.2 ± 2.5	20.8 ± 2.2	2.4 ± 0.24	<.0001
Medial condyle width, mm	26.5 ± 1.7	23.7 ± 1.6	2.8 ± 0.17	<.0001
Lateral condyle width, mm	25.6 ± 1.7	22.5 ± 1.5	3.1 ± 0.16	<.0001
NWI	0.304 ± 0.019	0.305 ± 0.024	0.001 ± 0.002	.509
LCFCR, mm	21.5 ± 1.5	19.2 ± 1.2	2.3 ± 0.13	<.0001
LCECR, mm	32.6 ± 3.1	29.7 ± 3.0	2.9 ± 0.30	<.0001
LFCI	0.66 ± 0.15	0.65 ± 0.15	0.03 ± 0.01	.034
MPPTA, deg	83.6 ± 3.5	83.1 ± 3.7	0.48 ± 0.37	.193
LPPTA, deg	84.1 ± 3.5	85.3 ± 2.9	1.23 ± 0.32	<.0001
ΔPPTA	3.20 ± 2.48	3.76 ± 2.66	0.56 ± 0.26	.031

[a]Values are expressed as mean ± SD. LCECR, lateral condylar extension circle radius; LCFCR, lateral condylar flexion circle radius; LFCI, lateral femoral condylar index; LPPTA, lateral posterior plateau tibial angle; MPPTA, medial posterior plateau tibial angle; NWI, notch width index; ΔPPTA, difference between LPPTA and MPPTA.

(AD = 3.1 ± 0.16 mm; *P* < .0001) condylar width, intercondylar notch width (AD = 2.4 ± 0.24 mm; *P* < .0001), LCFCR (AD = 2.3 ± 0.13 mm; *P* < .0001), LCECR (AD = 2.9 ± 0.30 mm; *P* < .0001), LFCI (AD = 0.03 ± 0.01; *P* = .034), LPPTA (AD = 1.23 ± 0.32°; *P* < .0001), and ΔPPTA (AD = 0.56 ± 0.26; *P* = .031) (Table 4). For the previously published thresholds, 4.7% of men versus 20.4% of women had an intercondylar notch width <20.2 mm, 12% of men versus 13.1% of women had NWI <0.292, 25.1% of men versus 37.2% of women had LFCI <0.67, 23.6% of men versus 27.8% of women had MPPTA <83.6°, and 20% of men versus 4.7% of women had LPPTA <81.6°.

Regarding ethnicity subgroups, significant differences could be identified between White and Asian participants for lateral condylar width (AD = 0.74 ± 0.23 mm; *P* = .001), intercondylar notch width (AD = 1.50 ± 0.26 mm; *P* < .0001), NWI (AD = 0.006 ± 0.002; *P* = .015), LCECR (AD = 1.13 ± 0.34 mm; *P* = .001), LFCI (AD = 0.03 ± 0.02; *P* = .036), and MPPTA (AD = 2.63° ± 0.35°; *P* < .01) (Table 5). For the previously published thresholds, 9.4% of White versus 15.7% of Asians had an intercondylar notch width <20.2 mm, 8.9% of White versus 16.2% of Asians had NWI <0.292, 33.5% of White versus 28.8% of Asians had LFCI <0.67, 17.3% of White versus 34% of Asians had MPPTA <83.6°, and 6.3% of White versus 8.9% of Asians had LPPTA <81.6°.

The multivariate regression analysis, including only the previously identified anatomic variables and controlling for confounding variables, confirmed the statistically significant relationship between sex and the medial and lateral condylar width (*P* < .0001), the intercondylar notch width (*P* < .0001), and the LCFCR and LCECR (*P* < .0001). LPPTA, NWI, and LFCI were not significant, independent predictors according to sex (Table 6).

TABLE 5

Univariate Analysis Estimating Mean Distal Femoral Values and Absolute Differences Between White and Asian Participants[a]

	White (n = 196)	Asian (n = 186)	Absolute Difference	P Value
Intercondylar notch width, mm	22.7 ± 2.7	21.2 ± 2.3	1.50 ± 0.26	<.0001
Medial condyle width, mm	25.1 ± 2.0	24.9 ± 2.4	0.23 ± 0.22	.290
Lateral condyle width, mm	24.3 ± 2.2	23.6 ± 2.3	0.74 ± 0.23	.001
NWI	0.307 ± 0.278	0.302 ± 0.013	0.006 ± 0.002	.015
LCFCR, mm	20.4 ± 1.8	20.1 ± 1.8	0.31 ± 0.18	.085
LCECR, mm	31.6 ± 3.5	30.5 ± 3.0	1.13 ± 0.34	.001
LFCI	0.64 ± 0.15	0.66 ± 0.14	0.03 ± 0.02	.036
MPPTA, deg	84.6 ± 3.3	81.9 ± 3.5	2.63 ± 0.35	<.01
LPPTA, deg	84.8 ± 3.0	84.8 ± 3.3	0.07 ± 0.32	.832
ΔPPTA	3.39 ± 2.44	3.53 ± 2.60	0.14 ± 0.26	.593

[a]Values are expressed as mean ± SD. LCECR, lateral condylar extension circle radius; LCFCR, lateral condylar flexion circle radius; LFCI, lateral femoral condylar index; LPPTA, lateral posterior plateau tibial angle; MPPTA, medial posterior plateau tibial angle; NWI, notch width index; ΔPPTA, difference between LPPTA and MPPTA.

TABLE 6

Results of Multivariate Analysis Regarding Factors That Influenced Absolute Differences[a]

Confounding Factors for Absolute Difference	Intercondylar Notch Width	Medial Condyle Width	Lateral Condyle Width	NWI	LCFCR	LCECR	LFCI	MPPTA	LPPTA	ΔPPTA
Sex	$P < .0001$	$P < .0001$	$P < .0001$	NS	$P < .0001$	$P < .0001$	NS	NS	NS	NS
Age	NS	$P = .001$ $R^2 = -0.001$	$P < .0001$ $R^2 = 0.01$	NS	$P = .006$ $R^2 = 0.004$	NS	NS	NS	NS	NS
Body mass index	NS	$P = .018$ $R^2 = 0.11$	$P = .001$ $R^2 = 0.13$	NS	NS	NS	NS	NS	NS	NS
Ethnicity	$P < .0001$	$P = .001$	$P < .0001$	NS	$P = .001$	$P < .0001$	$P = .012$	$P = .002$	NS	NS

[a]All P values were calculated using multiple analyses of variance. LCECR, lateral condylar extension circle radius; LCFCR, lateral condylar flexion circle radius; LFCI, lateral femoral condylar index; LPPTA, lateral posterior plateau tibial angle; MPPTA, medial posterior plateau tibial angle; NS, not significant; NWI, notch width index; ΔPPTA, difference between LPPTA and MPPTA.

Ethnicity was associated with significant differences between White and Asian participants for all parameters except for LPPTA and ΔPPTA in multivariate testing (Table 6). A significant correlation was found between femoral condylar width, AD, and BMI (respectively, $P = .018$ and $P = .001$). A weak relationship could be identified between medial and lateral condylar width and LCFCR with age (respectively, $P = .001$, $P < .0001$, and $P = .006$) (Table 6).

DISCUSSION

The main finding of this study is the high proportion of healthy participants who should be considered at risk of ACL injury according to the previously published femoral and tibial anatomic morphological values. Substantial variations of these parameters were found according to sex (intercondylar notch width) and ethnicity (intercondylar notch width, LFCI, MPPTA).

Reported values for bony risk factors vary from one study to another, making it difficult to provide clinical recommendations for prevention or preventive treatments[5] to reduce the risk of ACL injuries. In the present study, a high rate of healthy participants showed abnormal femoral and tibial bony morphological risk factors. This raises the question of their effective specificity and sensitivity in identifying which participants have a higher risk of sustaining an ACL injury or a graft rupture after ACL reconstruction.

A narrow notch is a recognized risk factor in patients sustaining an ACL injury.[31] Souryal et al[33] showed that the NWI was significantly smaller in patients with bilateral ACL (0.196) ruptures compared with those with unilateral ACL ruptures (0.225) or healthy controls (0.234). The reported mean NWI was higher in the present study (0.305) compared with the accepted threshold risk value (0.196).

Hodel et al[13] demonstrated an association between a decreased LFCI and ACL injury. This ratio indicates the normal spherical shape of the lateral condyle, which, when reduced, can be responsible for an abnormal pivoting mechanism. Hodel et al reported an LFCI of 0.67 in patients with ACL rupture and 0.76 in a control group.

In our study, a lower LFCI was observed (0.65) with a higher LCECR than the LCFCR. Conversely, Pfeiffer et al[24] reported an increased posterior femoral condylar depth (corresponding to a less spherical femoral condyle) in patients with ACL injury. A meta-analysis showed that both medial and lateral slopes changes were associated with higher risk of ACL injury. Stijak et al,[34] however, demonstrated an increased lateral tibial slope in patients with ACL injuries compared with control participants without substantial differences in the medial tibial slope. Hashemi et al[11] demonstrated similar results with a mean lateral tibial slope of 9° in the injured population. Similarly, Grassi et al[10] found that lateral posterior tibial slope was a significant independent predictor for graft failure after ACL reconstruction. This may be because of the increased trend toward an anterior displacement of the tibia. More recently, some authors have shown that patients with posterior tibial slope >10° had a higher rate of subsequent graft tear, leading the investigators to consider osteotomy in these cases to prevent retear.[27]

All of these anatomic parameters may play a role in the pathogenesis of ACL tears; however, it should be noted that "normal" differences exist according to sex and ethnicity. For example, the intercondylar notch is wider in men than in women,[6,17,20,28,30] which may explain the higher prevalence of ACL injuries in women.[12,22,32] Concerning ethnicity, it has been shown that African Americans have larger intercondylar notch width than White participants.[29] In the present study, a wider intercondylar notch was reported in White compared with Asian participants.

In the present series, LPPTA was different between men and women on univariate analysis (84.1 ± 0.2 vs 85.3 ± 2.2, respectively) in keeping with previously reported results.[11] In healthy participants, Hashemi et al found a lateral posterior tibial slope of 5.40° in men (LPPTA = 84.6°) and 7.03° in women (LPPTA = 82.97°). However, multivariate regression analysis showed that lateral posterior tibial slope was not a predictive factor for differences according to sex. Our study identified LFCI as a positive predictive factor for significant differences between ethnicities. Trojian and Collins[35] were the first to report different ACL tear rates in different ethnic and racial groups; those investigators found that Asian women had lower rates than White European American women.[35] The results of the present study showed that only femoral anatomic features and specifically LFCI were slightly different between White and Asian participants, but the clinical effect may be small (absolute LFCI difference = 0.02).

The current study has several limitations that could affect the reported results. First, because of the retrospective nature of the database evaluation, it was not possible to incorporate any information regarding participants' behaviors such as sport and activity level. Second, only asymptomatic participants were included in this cohort, and they may not perfectly match patients with ACL-deficient knees in terms of anatomic parameters. This database excluded patients who had undergone ACL reconstruction but may have included participants who had an asymptomatic ACL injury or who sustained an ACL injury at a later stage. Some participants might have had degenerative changes that may have affected some parameters. Third, some bony factors were not evaluated in the present study given that the CT scan–based modeling and analysis system did not allow inclusion of all anatomic morphological parameters. Fourth, the results of this study cannot be generalized to the general population. Extreme age values were included, which are not representative of patients who have surgery for an ACL injury, but multivariate analysis showed that there was no correlation between the participants' age and the main bony risk factors for ACL injury. Some values were influenced by age and BMI of the participants, suggesting the dynamic contribution of these variables, but BMI and age did not influence the main ACL bony risk factors (NWI, LFCI, MPPTA, and LPPTA). The lack of inclusion of African descent participants, because of lack of data, also does not allow us to generalize the results of this study. This population is underrepresented in the literature,[18] and it has been demonstrated that White patients had narrower notches than African American men.[29] The threshold values defined in this study may vary according to the ethnicity of the participants, and we did not perform the African and Middle Easterners subgroup analysis. Additional studies taking into account the ethnicity of the participants will have to be carried out before any conclusions can be made. The method of measuring bony values in this study was not strictly comparable with those used in the referenced studies, but there is no gold standard for such measurements. In addition, measurements derived from CT-scans are necessarily different from those derived from radiographs but have the advantage in this study of being reliable and reproducible.

The present study has some notable and relevant aspects. First, the reported values are clinically accepted and refer to a large demographic group in the published literature, which allowed for a secondary analysis with statistical power. Second, the study was based on 3-dimensional CT analysis, which has been shown to be more accurate than 2-dimensional CT analysis for measurements of the lateral and medial tibial slopes and intercondylar notch width. The improved accuracy provided by this system allowed for improved reliability of the reported values.

Based on these findings, a significant proportion of healthy participants reached the thresholds considered to be at risk of ACL injury. Only 14.4% of participants had no ACL bony risk factor, and for some parameters, >50% of the population exhibited values exceeding defined normal values. Indeed, it seems to be difficult to correlate the clinical risk with bony morphological risk factors.

CONCLUSION

Precise definition of femoral and tibial anatomic risk factors for ACL injury is difficult. According to the thresholds that are usually reported in the literature, 15% to 62% of a healthy reference population should be considered as being at risk for an ACL injury. This rate is probably too high, and the generally reported thresholds may be misleading. Sensitivity and specificity analyses of large cohorts are therefore necessary to precisely define which participants with so-called bony abnormalities would really be at risk of sustaining ACL injuries and experiencing ACL reconstruction failures.

REFERENCES

1. Banerjee S, Faizan A, Nevelos J, et al. Innovations in hip arthroplasty three-dimensional modeling and analytical technology (SOMA). *Surg Technol Int*. 2014;24:288-294.
2. Brandon ML, Haynes PT, Bonamo JR, Flynn MI, Barrett GR, Sherman MF. The association between posterior-inferior tibial slope and anterior cruciate ligament insufficiency. *Arthroscopy*. 2006;22(8):894-899. doi:10.1016/j.arthro.2006.04.098
3. Burnham JM, Pfeiffer T, Shin JJ, Herbst E, Fu FH. Bony morphologic factors affecting injury risk, rotatory stability, outcomes, and re-tear rate after anterior cruciate ligament reconstruction. *Ann Joint*. 2017;2:44-44. doi:10.21037/aoj.2017.06.11
4. Christensen JJ, Krych AJ, Engasser WM, Vanhees MK, Collins MS, Dahm DL. Lateral tibial posterior slope is increased in patients with early graft failure after anterior cruciate ligament reconstruction. *Am J Sports Med*. 2015;43(10):2510-2514. doi:10.1177/0363546515597664
5. Dejour D, Saffarini M, Demey G, Baverel L. Tibial slope correction combined with second revision ACL produces good knee stability and prevents graft rupture. *Knee Surg Sports Traumatol Arthrosc*. 2015;23(10):2846-2852. doi:10.1007/s00167-015-3758-6
6. Dienst M, Schneider G, Altmeyer K, et al. Correlation of intercondylar notch cross sections to the ACL size: a high resolution MR tomographic in vivo analysis. *Arch Orthop Trauma Surg*. 2007;127(4):253-260. doi:10.1007/s00402-006-0177-7
7. Eck CFV, Martins CAQ, Vyas SM, Celentano U, van Dijk CN, Fu FH. Femoral intercondylar notch shape and dimensions in ACL-injured patients. *Knee Surg Sports Traumatol Arthrosc*. 2010;18(9):1257-1262. doi:10.1007/s00167-010-1135-z
8. Fernandes MS, Pereira R, Andrade R, et al. Is the femoral lateral condyle's bone morphology the trochlea of the ACL? *Knee Surg Sports Traumatol Arthrosc*. 2017;25(1):207-214. doi:10.1007/s00167-016-4159-1
9. Feucht MJ, Mauro CS, Brucker PU, Imhoff AB, Hinterwimmer S. The role of the tibial slope in sustaining and treating anterior cruciate ligament injuries. *Knee Surg Sports Traumatol Arthrosc*. 2013;21(1):134-145. doi:10.1007/s00167-012-1941-6
10. Grassi A, Signorelli C, Urrizola F, et al. Patients with failed anterior cruciate ligament reconstruction have an increased posterior lateral tibial plateau slope: a case-controlled study. *Arthroscopy*. 2019;35(4):1172-1182. doi:10.1016/j.arthro.2018.11.049
11. Hashemi J, Chandrashekar N, Mansouri H, et al. Shallow medial tibial plateau and steep medial and lateral tibial slopes: new risk factors for anterior cruciate ligament injuries. *Am J Sports Med*. 2010;38(1):54-62. doi:10.1177/0363546509349055
12. Hewett TE, Myer GD, Ford KR. Anterior cruciate ligament injuries in female athletes, part 1: mechanisms and risk factors. *Am J Sports Med*. 2006;34(2):299-311. doi:10.1177/0363546505284183
13. Hodel S, Kabelitz M, Tondelli T, Vlachopoulos L, Sutter R, Fucentese SF. Introducing the lateral femoral condyle index as a risk factor for anterior cruciate ligament injury. *Am J Sports Med*. 2019;47(10):2420-2426. doi:10.1177/0363546519858612
14. Hohmann E, Bryant A, Reaburn P, Tetsworth K. Is there a correlation between posterior tibial slope and non-contact anterior cruciate ligament injuries? *Knee Surg Sports Traumatol Arthrosc*. 2011;19(suppl 1):109-114. doi:10.1007/s00167-011-1547-4
15. Hoteya K, Kato Y, Motojima S, et al. Association between intercondylar notch narrowing and bilateral anterior cruciate ligament injuries in athletes. *Arch Orthop Trauma Surg*. 2011;131(3):371-376. doi:10.1007/s00402-010-1254-5
16. International Olympic Committee Pediatric ACL Injury Consensus Group; Ardern CL, Ekås G, et al. 2018 International Olympic Committee consensus statement on prevention, diagnosis, and management of pediatric anterior cruciate ligament injuries. *Orthop J Sports Med*. 2018;6(3):232596711875995. doi:10.1177/2325967118759953
17. Ireland ML, Ballantyne BT, Little K, McClay IS. A radiographic analysis of the relationship between the size and shape of the intercondylar notch and anterior cruciate ligament injury. *Knee Surg Sports Traumatol Arthrosc*. 2001;9(4):200-205. doi:10.1007/s001670100197
18. Kim TK, Phillips M, Bhandari M, Watson J, Malhotra R. What differences in morphologic features of the knee exist among patients of various races? A systematic review. *Clin Orthop Relat Res*. 2017;475(1):170-182. doi:10.1007/s11999-016-5097-4
19. Lee CC, Youm YS, Cho SD, et al. Does posterior tibial slope affect graft rupture following anterior cruciate ligament reconstruction? *Arthroscopy*. 2018;34(7):2152-2155. doi:10.1016/j.arthro.2018.01.058
20. Mahfouz M, Abdel Fatah EE, Bowers LS, Scuderi G. Three-dimensional morphology of the knee reveals ethnic differences. *Clin Orthop Relat Res*. 2012;470(1):172-185. doi:10.1007/s11999-011-2089-2
21. Musahl V, Ayeni OR, Citak M, Irrgang JJ, Pearle AD, Wickiewicz TL. The influence of bony morphology on the magnitude of the pivot shift. *Knee Surg Sports Traumatol Arthrosc*. 2010;18(9):1232-1238. doi:10.1007/s00167-010-1129-x
22. Myer GD, Ford KR, Paterno MV, Nick TG, Hewett TE. The effects of generalized joint laxity on risk of anterior cruciate ligament injury in young female athletes. *Am J Sports Med*. 2008;36(6):1073-1080. doi:10.1177/0363546507313572
23. Pedoia V, Lansdown DA, Zaid M, et al. Three-dimensional MRI-based statistical shape model and application to a cohort of knees with acute ACL injury. *Osteoarthritis Cartilage*. 2015;23(10):1695-1703. doi:10.1016/j.joca.2015.05.027
24. Pfeiffer TR, Burnham JM, Hughes JD, et al. An increased lateral femoral condyle ratio is a risk factor for anterior cruciate ligament injury: *J Bone Joint Surg Am*. 2018;100(10):857-864. doi:10.2106/JBJS.17.01011
25. Schmidt W, LiArno S, Khlopas A, Petersik A, Mont MA. Stryker Orthopaedic Modeling and Analytics (SOMA): a review. *Surg Technol Int*. 2018;32:315-324.
26. Schröder M, Gottschling H, Reimers N, Hauschild M, Burgkart R. Automated morphometric analysis of the femur on large anatomical databases with highly accurate correspondence detection. *Open Med J*. 2014;1(1):15-22. doi:10.2174/1874220301401010015
27. Shelbourne KD, Benner RW, Jones JA, Gray T. Posterior tibial slope in patients undergoing anterior cruciate ligament reconstruction with patellar tendon autograft: analysis of subsequent ACL graft tear or contralateral ACL tear. *Am J Sports Med*. 2021;49(3):620-625. doi:10.1177/0363546520982241
28. Shelbourne KD, Facibene WA, Hunt JJ. Radiographic and intraoperative intercondylar notch width measurements in men and women with unilateral and bilateral anterior cruciate ligament tears. *Knee Surg Sports Traumatol Arthrosc*. 1997;5(4):229-233. doi:10.1007/s001670050055
29. Shelbourne KD, Gray T, Benner RW. Intercondylar notch width measurement differences between African American and White men and women with intact anterior cruciate ligament knees. *Am J Sports Med*. 2007;35(8):1304-1307. doi:10.1177/0363546507300060
30. Shelbourne KD, Kerr B. The relationship of femoral intercondylar notch width to height, weight, and sex in patients with intact anterior cruciate ligaments. *Am J Knee Surg*. 2001;14(2):92-96.

31. Smith HC, Vacek P, Johnson RJ, et al. Risk factors for anterior cruciate ligament injury: a review of the literature, part 1: neuromuscular and anatomic risk. *Sports Health*. 2012;4(1):69-78. doi:10.1177/1941738111428281
32. Smith HC, Vacek P, Johnson RJ, et al. Risk factors for anterior cruciate ligament injury: a review of the literature, part 2: hormonal, genetic, cognitive function, previous injury, and extrinsic risk factors. *Sports Health*. 2012;4(2):155-161. doi:10.1177/1941738111428282
33. Souryal TO, Moore HA, Evans JP. Bilaterality in anterior cruciate ligament injuries: associated intercondylar notch stenosis. *Am J Sports Med*. 1988;16(5):449-454. doi:10.1177/036354658801600504
34. Stijak L, Herzog RF, Schai P. Is there an influence of the tibial slope of the lateral condyle on the ACL lesion? A case-control study. *Knee Surg Sports Traumatol Arthrosc*. 2008;16(2):112-117. doi:10.1007/s00167-007-0438-1
35. Trojian TH, Collins S. The anterior cruciate ligament tear rate varies by race in professional women's basketball. *Am J Sports Med*. 2006;34(6):895-898. doi:10.1177/0363546505284384
36. Webb JM, Salmon LJ, Leclerc E, Pinczewski LA, Roe JP. Posterior tibial slope and further anterior cruciate ligament injuries in the anterior cruciate ligament–reconstructed patient. *Am J Sports Med*. 2013;41(12):2800-2804. doi:10.1177/0363546513503288
37. Wratten CJE, Tetsworth K, Hohmann E. Three-dimensional femoral notch volume in anterior cruciate ligament–deficient versus anterior cruciate ligament–intact patients: a matched case-control study with inter-gender comparison. *Arthroscopy*. 2015;31(6):1117-1122. doi:10.1016/j.arthro.2014.12.014
38. Zhang C, Zhang X, Fang Z, et al. The correlation between common 2D femoral notch parameters and 3D notch volume: a retrospective MRI study. *BMC Musculoskelet Disord*. 2019;20(1):146. doi:10.1186/s12891-019-2530-3