Morphological Risk Factors for Pediatric Anterior Cruciate Ligament Tears and Tibial Spine Fractures

Chang Ho Shin, MD, Akbar N. Syed, MD, Morgan E. Swanson, BA,
J. Todd R. Lawrence, MD, PhD, Tibial Spine Research Interest Group, and Theodore J. Ganley,* MD
Investigation performed at Children's Hospital of Philadelphia, Philadelphia, Pennsylvania, USA

Background: Both tibial spine fractures (TSFs) and anterior cruciate ligament (ACL) tears result in functional loss of knee stability. Nonetheless, it remains unclear why some patients sustain ACL tears, whereas others have TSFs.

Purpose: To identify the common morphological risk factors for pediatric ACL tears and TSFs and to determine the morphological differences between them using multiplanar reconstruction of magnetic resonance imaging (MRI).

Study Design: Cohort study; Level of evidence, 3.

Methods: Age- and sex-matched participants (159 total [53 ACL tears, 53 TSFs, and 53 controls]) aged <18 years who visited a pediatric tertiary-care center for ACL tears, TSFs, or anterior knee pain from March 2009 to April 2023 were included. Each group comprised 41 male and 12 female participants. Data on demographic characteristics and estimated bone age based on the knee MRI atlas were retrospectively collected, and various knee morphological parameters were evaluated using multiplanar reconstruction of MRI. Parameters showing significant differences among the 3 groups were selected as independent variables for multivariable multinomial logistic regression analysis, with the groups as dependent variables.

Results: The mean chronological age at the time of MRI was 13.2 ± 2.3 years. Height, weight, body mass index, bone age, articular medial tibial slope, and bony medial tibial slope did not differ among the groups. Articular lateral tibial slope was independently associated with the occurrence of both ACL tears (relative risk ratio [RRR], 1.42 [95% confidence interval (CI), 1.16-1.74]; *P* = .001) and TSFs (RRR, 1.33 [95% CI, 1.10-1.62]; *P* = .004). A high notch width index was a protective factor against ACL tears (RRR, 0.86 [95% CI, 0.77-0.96]; *P* = .006) but not against TSFs (RRR, 1.01 [95% CI, 0.91-1.12]; *P* = .848).

Conclusion: A high articular lateral tibial slope was a common risk factor for ACL tears and TSFs. Patients with ACL tears had a narrower intercondylar notch than those with TSFs and controls.

Keywords: anterior cruciate ligament; tibial spine fracture; tibial slope; notch width; pediatric sports medicine

Tibial spine fractures (TSFs) are avulsion fractures of the anterior cruciate ligament (ACL) from its insertion on the intercondylar eminence of the tibia. Both TSFs and ACL tears result in functional loss of knee stability.[7,9,13,28] However, it remains unclear why some patients sustain ACL tears, while others have TSFs.

Researchers have investigated the demographic, biomechanical, endocrinological, and environmental risk factors for these injuries to explore their causes.[1,3,14] Various morphological risk factors for ACL tears and TSFs have also been examined by comparing patients with either ACL tears or TSFs and controls.[†] However, to the best of our knowledge, only 2 studies have compared knee morphology between patients with ACL tears and those with TSFs,[25,37] with relatively small sample sizes (25 ACL tears and 25 TSFs in both studies), and they reported contradictory results regarding the femoral intercondylar notch width. These studies evaluated only a few risk factors using radiography and did not employ magnetic resonance imaging (MRI), which can provide more detailed information on morphology, including that of cartilage and the meniscus. In addition, one of the studies did not have a control group, making it difficult to determine which patient group (ACL tears vs TSFs) had abnormal values.[25]

Therefore, a study comparing comprehensive morphological risk factors on MRI with larger samples of patients with ACL tears or TSFs and controls was conducted. Understanding the morphological similarities and differences between patients with ACL tears and those with TSFs may aid in comprehending the causes of these injuries, thereby allowing for better risk counseling. The current study aimed to identify the common morphological risk factors for ACL tears and TSFs and to determine the

[†]References 11, 15, 20, 26, 29, 32, 35, 39, 40, 45, 49.

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morphological differences between them using multiplanar reconstruction (MPR) of MRI.

METHODS

Patients

After receiving approval from the institutional review board, we conducted a retrospective cross-sectional study by searching a single large pediatric tertiary-care center database for patients who visited for TSFs from March 2009 to April 2023. Of 160 patients aged <18 years who had TSFs, 3 patients aged <7.5 years were excluded because of the small sample size and substantial differences in shape between the bone and cartilage in our pilot study. Furthermore, 102 patients without any preoperative thin-slice MRI of the knee (≤1 mm) were excluded because the slice thickness could affect the quality of MPR images used to create standardized measurement planes. Additionally, 2 patients were excluded because of poor MRI quality. Ultimately, 53 patients (41 male and 12 female) were included in the TSF group after confirming that they had no medical conditions/history that could possibly affect knee morphology (Figure 1).

During the same study period, we identified 1945 patients who underwent ACL reconstruction and 3692 controls who had anterior knee pain but did not have clinically significant findings on examination and imaging within the same age range as the patients in the TSF group (7.5-18 years). Of these, we randomly selected 53 patients who underwent ACL reconstruction (ACL group) and 53 controls with anterior knee pain (control group), who were matched by age (±1.0 years) and sex to the patients in the TSF group. Randomization was performed using a random number generator (Excel; Microsoft). A patient who did not undergo thin-slice MRI was excluded, and another age- and sex-matched patient was then randomly selected because the quality of MPR images was insufficient for creating standardized measurement planes. Additionally, a patient with medical conditions/history that could possibly affect knee morphology was excluded, and another patient was randomly selected. Ultimately, 159 participants (53 patients with TSFs, 53 patients with ACL tears, and 53 controls) were included in this study.

MRI Protocol

Patients underwent MRI using either a 3.0- or 1.5-T magnet (Siemens Healthineers). The participants were placed in the supine position with their knees in full or near-full extension based on their comfort level. The routine knee MRI protocol included axial and coronal fat-suppressed intermediate-weighted turbo spin echo (TSE), sagittal non–fat-suppressed proton density–weighted TSE, sagittal and coronal non–fat-suppressed T1-weighted TSE, sagittal fat-suppressed T2-weighted TSE, and sagittal 3-dimensional double echo steady state (3D-DESS) sequences. The sagittal 3D-DESS sequence parameters were as follows: repetition time, 17.02 milliseconds; echo time, 4.87 milliseconds; flip angle, 25°; slice thickness, 0.7 mm; matrix, 320 × 320; and pixel bandwidth, 210 Hz. The field of view was adjusted according to the size of the patient.

Data Collection

Demographic data including age, sex, race, laterality, height, weight, and body mass index were recorded. In the TSF group, the fracture type was categorized using knee radiography according to Zaricznyj's[48] modification of the Meyers and McKeever classification.

Bone age was determined using sagittal and coronal non–fat-suppressed T1-weighted TSE MRI based on the shorthand knee MRI atlas for bone age estimation by Meza et al.[30] If patients did not achieve the milestones for 10 years, they were recorded as 9 years old based on the instructions of the atlas.

Sagittal 3D-DESS MRI was used to create MPR images to measure the morphological parameters of the knee. All morphological parameters measured in the current study have been reported as risk factors for either ACL tears or TSFs in previous studies.[‡] Detailed information on creating standardized measurement planes, defining the coronal and sagittal longitudinal axes of the femur and tibia, and measuring parameters is provided in the Appendix (available in the online version of this article).

On the sagittal image reflecting the center of the medial compartment of the tibiofemoral joint, the posterior slope

‡References 2, 5, 11, 16, 20, 21, 23, 34, 39-41, 47, 49.

*Address correspondence to Theodore J. Ganley, MD, Children's Hospital of Philadelphia, 3401 Civic Center Boulevard, Philadelphia, PA 19104, USA (email: ganley@chop.edu).

All authors are listed in the Authors section at the end of the article.

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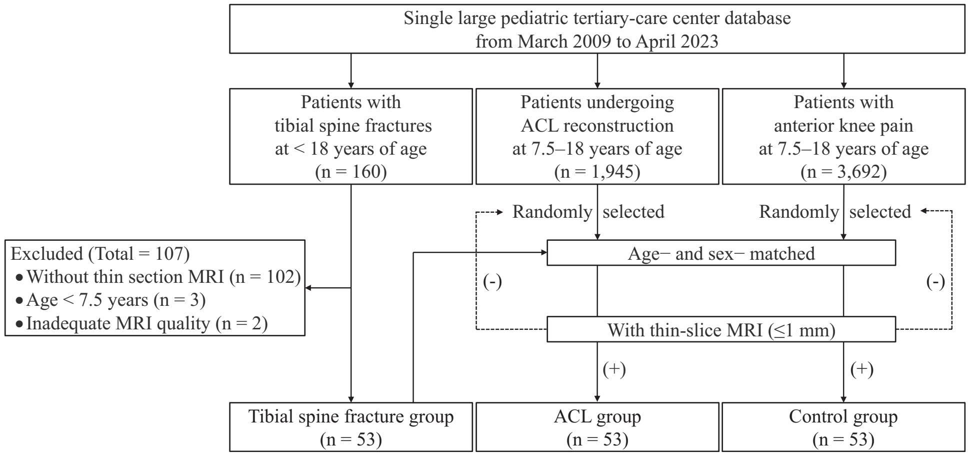

Figure 1. Flowchart of the study population. ACL, anterior cruciate ligament; MRI, magnetic resonance imaging.

of the articular surface of the medial tibial plateau (articular medial tibial slope [MTS]),[11] the posterior slope of the subchondral bone of the medial tibial plateau (bony MTS),[20] and the medial tibial depth[20] were measured (Figure 2). The articular MTS was defined as the angle between a line perpendicular to the sagittal tibial longitudinal axis and a line connecting the posterior aspect of the anterior horn and posterior aspect of the posterior horn of the medial meniscus at its interface with articular cartilage. The bony MTS was defined as the angle between a line perpendicular to the sagittal tibial longitudinal axis and a line connecting the peak anterior and posterior points on the bony medial tibial plateau. The medial tibial depth was defined as the perpendicular distance between a line connecting the peak anterior and posterior points on the bony medial tibial plateau and the lowest point of concavity.

The posterior slope of the articular surface of the lateral tibial plateau (articular lateral tibial slope [LTS]),[11] posterior slope of the subchondral bone of the lateral tibial plateau (bony LTS),[20] lateral compartment middle cartilage slope (LMCS),[41] lateral compartment meniscus-bone angle (LMBA),[41] and lateral compartment meniscus-cartilage height (LMCH)[41] were measured on the sagittal image reflecting the center of the lateral compartment of the tibiofemoral joint. The articular LTS was defined as the angle between a line perpendicular to the sagittal tibial longitudinal axis and a line connecting the anterior aspect of the anterior horn and posterior aspect of the posterior horn of the lateral meniscus at its interface with articular cartilage. The bony LTS was defined as the angle between a line perpendicular to the sagittal tibial longitudinal axis and a line connecting the peak anterior and posterior points on the bony lateral tibial plateau. The LMCS was defined as the angle between a line joining the most superior, anterior, and posterior prominences of the middle articular cartilage surface of the lateral tibial plateau and a line perpendicular to the sagittal tibial longitudinal axis. The LMBA was defined as the angle between a line tangent to the superior posterolateral surface of the posterior horn of the lateral meniscus and a line connecting the peak anterior and posterior points on the bony lateral tibial plateau. The LMCH was defined as the distance between the most superior point of the posterior horn of the lateral meniscus and underlying articular cartilage surface.

The lateral femoral condyle ratio (LFCR)[21,34,49] was measured on the sagittal image reflecting the center of the lateral femoral condyle. A line was drawn from the most anterior to posterior point of the lateral condyle, defined as the length of the femoral condylar axis. The distance from the intersection of the sagittal femoral and femoral condylar longitudinal axes to the most posterior point of the lateral condyle was divided by the length of the femoral condylar axis and multiplied by 100%. This percentage was determined as the LFCR.

For the intercondylar notch of the femur, the alpha angle,[5] notch angle,[23] notch shape,[5] and notch width index (NWI)[47] were evaluated. The alpha angle was defined as the angle between the sagittal femoral longitudinal axis and a line tangent to the Blumensaat line on the midsagittal image of the femur. The notch angle was defined as the angle between 2 lines, starting from the most anterior point of the intercondylar notch to the medial or lateral condylar margin of the intercondylar notch in the axial plane. The notch shape was classified as either type A or U in the axial plane. A type A notch shape was defined as a narrow stenotic notch from the midsection to the base and apex, whereas a type U notch shape was defined as having a wider contour, such that the midsection did not taper from the base. The current study did not identify any patients with a type W notch shape in the study population. The NWI was measured in the coronal oblique plane parallel to the Blumensaat line on the midsagittal image. A baseline was drawn tangent to the posterior subchondral aspect of both femoral condyles in the coronal oblique plane. The intercondylar notch width at the anterior outlet and the bicondylar width were measured parallel to the baseline. The NWI was defined as the ratio of notch width to bicondylar width multiplied by 100% ([NW/BW] $\times$ 100%).[23,47]

The measurements were conducted by the first author (C.H.S.), who is a board-certified pediatric orthopaedic

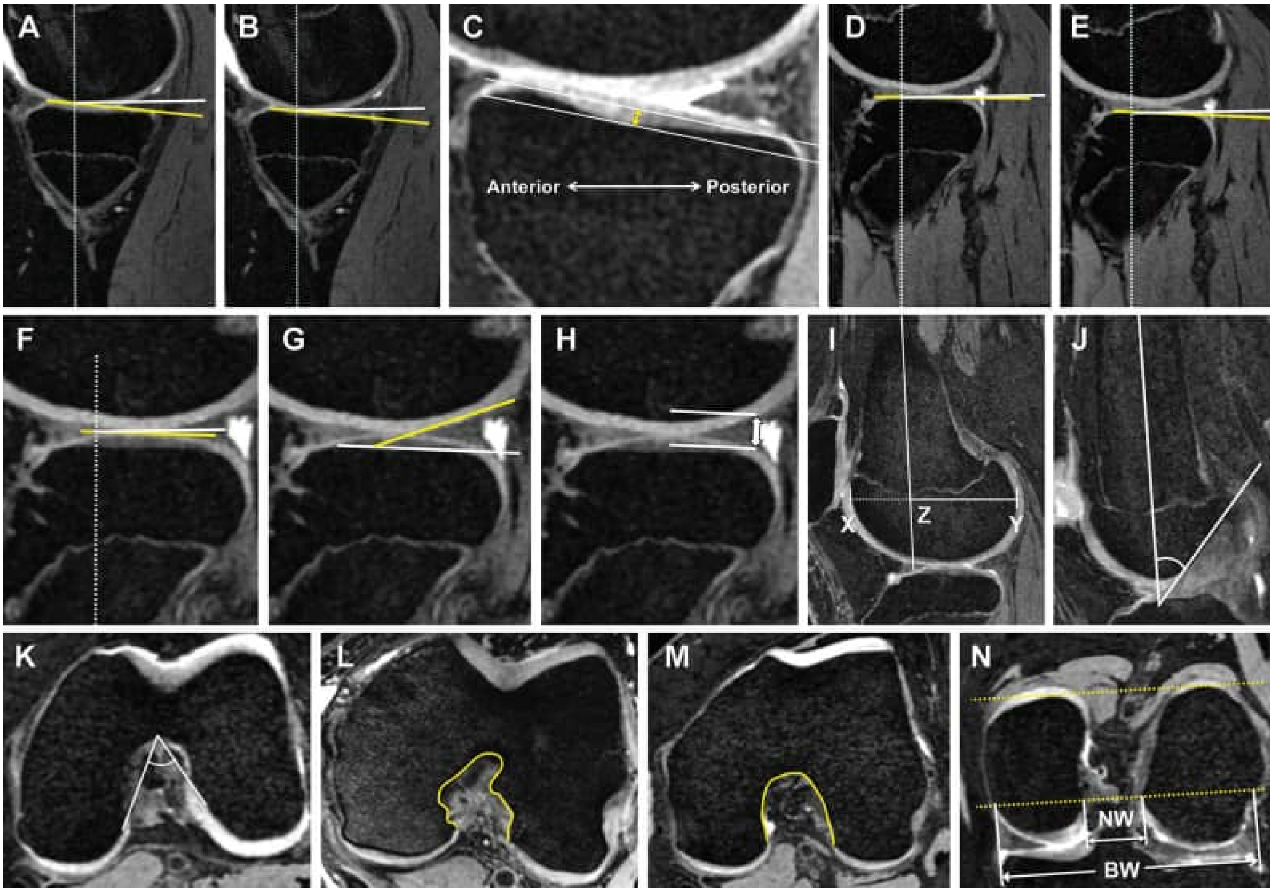

Figure 2. Evaluation methods for morphological parameters of the knee. (A) Articular medial tibial slope, (B) bony medial tibial slope, (C) medial tibial depth, (D) articular lateral tibial slope, (E) bony lateral tibial slope, (F) lateral compartment middle cartilage slope, (G) lateral compartment meniscus-bone angle, (H) lateral compartment meniscus-cartilage height, (I) lateral femoral condyle ratio ([length of line YZ/length of line XY] × 100%), (J) alpha angle, (K) notch angle, (L) type A notch shape, (M) type U notch shape, and (N) notch width index ([NW/BW] × 100%). BW, bicondylar width; NW, notch width.

surgeon. To determine intraobserver and interobserver reliability, on a different day from the first measurement day, 4 weeks apart, the first author re-estimated the bone age and remeasured the morphological parameters of 30 randomly selected patients. The second author (A.N.S.), also a board-certified pediatric orthopaedic surgeon, assessed the bone age and measured all parameters of these 30 patients after a consensus-building session on measurements. All radiological evaluations were performed using the NilRead PACS viewer (Version 5.1.10; Hyland Software).

Statistical Analysis

Intraobserver and interobserver reliability were examined using the intraclass correlation coefficient (ICC; absolute-agreement, single-measurement, 2-way random-effects model) for bone age and morphological parameters, except for notch shape. The reliability of notch shape was assessed using the Cohen kappa coefficient. An ICC <0.40 was considered poor; 0.40-0.59, fair; 0.60-0.75, good; and >0.75, excellent.[17] A kappa value ≤ 0.20 was considered slight agreement; 0.21-0.40, fair agreement; 0.41-0.60, moderate agreement; 0.61-0.80, substantial agreement; and 0.81-1.00, almost perfect agreement.[27]

Continuous variables were compared among the 3 groups using 1-way analysis of variance and the Tukey post hoc test or Kruskal-Wallis test and Dunn post hoc test with the Benjamini-Hochberg adjustment, after performing the Shapiro-Wilk test for normality and the Bartlett test for homogeneity of variances. Categorical variables were compared among groups using the chi-square test or Fisher exact test. Univariable multinomial logistic regression analysis was performed, with demographic/morphological parameters or bone age as the independent variables and the 3 groups as the dependent variables. Parameters showing significant differences among the groups on 1-way analysis of variance, the Kruskal-Wallis test, the chi-square test, or the Fisher exact test as well as parameters with a P value $<.1$ on univariable multinomial logistic regression analysis were selected as independent variables for multivariable multinomial logistic regression analysis. On multinomial logistic

TABLE 1
Participant Characteristics and MRI Parameters[a]

	ACL (n = 53)	TSF (n = 53)	Control (n = 53)	*P* Value
Age at MRI, y	13.2 ± 2.3 (7.7 to 17.8)	13.3 ± 2.4 (7.7 to 17.6)	13.2 ± 2.4 (7.9 to 17.5)	.993[b]
Sex, male/female	41/12 (77/23)	41/12 (77/23)	41/12 (77/23)	>.999[c]
Laterality, right/left	24/29 (45/55)	30/23 (57/43)	32/21 (60/40)	.268[c]
Race				.576[c]
White	24 (45)	20 (38)	26 (49)	
Black	22 (42)	25 (47)	17 (32)	
Other	7 (13)	8 (15)	10 (19)	
Height, cm	160.5 ± 15.2 (129.6 to 188.9)	161.0 ± 15.6 (118.0 to 180.8)	159.1 ± 15.5 (128.9 to 188.3)	.637[d]
Weight, kg	59.9 ± 19.9 (25.1 to 97.5)	55.2 ± 15.1 (23.3 to 90.7)	59.1 ± 26.0 (24.5 to 161.8)	.452[d]
Body mass index, kg/m^2	22.7 ± 4.9 (14.9 to 35.7)	21.1 ± 4.7 (14.9 to 41.8)	22.5 ± 6.4 (14.5 to 45.6)	.182[d]
Bone age, y	13.7 ± 2.5 (9.0 to 17.0)	13.3 ± 2.1 (9.0 to 17.0)	13.3 ± 2.5 (9.0 to 17.0)	.657[b]
Medial compartment				
Articular MTS, deg	7.0 ± 2.8 (0.8 to 14.1)	8.2 ± 2.9 (2.7 to 13.7)	7.1 ± 3.0 (0.0 to 15.0)	.089[b]
Bony MTS, deg	6.0 ± 2.8 (0.2 to 13.0)	7.4 ± 3.1 (0.7 to 13.5)	6.9 ± 3.1 (0.0 to 16.4)	.054[b]
Medial tibial depth, mm	2.1 ± 0.9 (0.0 to 6.0)	1.8 ± 0.8 (0.0 to 10.0)	1.8 ± 1.2 (0.0 to 5.0)	.055[b]
Lateral compartment				
Articular LTS, deg	7.1 ± 4.5 (–3.4 to 18.1)	6.6 ± 3.2 (0.2 to 15.7)	3.0 ± 4.3 (–6.0 to 15.0)	**<.001**[b]
Bony LTS, deg	7.1 ± 3.2 (–1.7 to 12.9)	6.9 ± 3.4 (–2.8 to 12.8)	5.2 ± 3.2 (0.0 to 13.8)	**.002**[d]
LMCS, deg	7.1 ± 3.5 (–0.5 to 15.0)	6.7 ± 3.0 (0.7 to 14.7)	5.1 ± 4.0 (–3.2 to 15.0)	**.008**[b]
LMBA, deg	21.9 ± 6.4 (6.3 to 31.3)	22.0 ± 5.9 (6.2 to 34.4)	25.0 ± 4.8 (17.0 to 41.0)	**.018**[d]
LMCH, mm	6.5 ± 1.4 (4.0 to 11.0)	6.7 ± 1.5 (5.0 to 11.0)	6.9 ± 1.2 (5.0 to 11.0)	.215[d]
LFCR, %	59.5 ± 3.9 (44.6 to 67.3)	58.5 ± 2.8 (52.3 to 65.1)	60.6 ± 3.2 (52.6 to 71.6)	**.006**[d]
Intercondylar notch				
Alpha angle, deg	44.6 ± 6.6 (32.0 to 66.0)	43.5 ± 5.1 (31.0 to 55.9)	42.0 ± 5.7 (28.0 to 55.0)	.072[b]
Notch angle, deg	53.5 ± 12.1 (29.3 to 81.4)	53.3 ± 10.1 (34.1 to 75.0)	58.9 ± 13.0 (30.0 to 88.0)	**.024**[b]
Notch shape, type U/A	30/23 (57/43)	35/18 (66/34)	40/13 (75/25)	.122[c]
NWI, %	23.7 ± 5.0 (12.6 to 34.2)	26.3 ± 4.8 (19.3 to 40.1)	27.0 ± 5.2 (14.5 to 43.8)	**.009**[d]

[a]Data are presented as mean ± SD (range) or n (%). Bold font indicates statistical significance. ACL, anterior cruciate ligament; LFCR, lateral femoral condyle ratio; LMBA, lateral compartment meniscus-bone angle; LMCH, lateral compartment meniscus-cartilage height; LMCS, lateral compartment middle cartilage slope; LTS, lateral tibial slope; MRI, magnetic resonance imaging; MTS, medial tibial slope; NWI, notch width index; TSF, tibial spine fracture.
[b]One-way analysis of variance.
[c]Chi-square test.
[d]Kruskal-Wallis test.

regression analysis, regression coefficients were expressed as relative risk ratios (RRRs) with corresponding 95% confidence intervals (CIs).

A receiver operating characteristic curve was used to determine the cutoff values for the parameters that distinguished the groups on multinomial logistic regression analysis. Statistical significance was set at $P < .05$. Statistical analyses were performed using Stata (Version 18.0; StataCorp).

RESULTS

Demographic characteristics and bone age did not differ among the groups (Table 1). The TSF group included 1 patient (2%) with a type I fracture, 10 (19%) with a type II fracture, 37 (70%) with a type III fracture, and 5 (9%) with a type IV fracture (see Appendix Table A1, available online).

The intraobserver and interobserver reliability of bone age, articular MTS, bony MTS, medial tibial depth, articular LTS, and notch angle were excellent (ICC = 0.753-0.992) (see Appendix Table A2, available online). The intraobserver and interobserver reliability of bony LTS, LMBA, and LMCH were good (ICC = 0.672-0.749). The LMCS, alpha angle, and NWI showed excellent interobserver reliability (ICC = 0.765-0.840) but good intraobserver reliability (ICC = 0.620-0.741). The LFCR exhibited excellent interobserver reliability (ICC = 0.769 [95% CI, 0.516-0.890]) but fair intraobserver reliability (ICC = 0.534 [95% CI, 0.215-0.748]). The notch shape showed moderate intraobserver (kappa = 0.59; 83% agreement) and interobserver (kappa = 0.59; 83% agreement) reliability.

Morphological parameters for the lateral compartment of the tibiofemoral joint, including the articular LTS, bony LTS, LMCS, LMBA, and LFCR, as well as parameters for the intercondylar notch, including the notch angle and NWI, differed among the groups (Table 1). However, no differences were observed in medial compartment parameters. Post hoc tests revealed that the articular LTS, bony LTS, and LMCS were higher, while the LMBA was lower, in the ACL and TSF groups than in the control group (see Appendix Table A3, available online). The LFCR and notch angle were lower in the TSF group than in the

TABLE 2
Multivariable Multinomial Logistic Regression Analysis[a]

	ACL vs Control		TSF vs Control	
	RRR (95% CI)	*P* Value	RRR (95% CI)	*P* Value
Medial compartment				
Medial tibial depth	0.90 (0.61-1.33)	.598	0.74 (0.49-1.12)	.158
Lateral compartment				
Articular LTS	1.42 (1.16-1.74)	**.001**	1.33 (1.10-1.62)	**.004**
LMCS	0.87 (0.71-1.07)	.183	0.87 (0.71-1.06)	.174
LMBA	0.94 (0.87-1.02)	.134	0.94 (0.86-1.02)	.12
LFCR	1.04 (0.90-1.21)	.607	0.87 (0.74-1.01)	.07
Intercondylar notch				
Alpha angle	1.08 (0.99-1.18)	.069	1.02 (0.94-1.12)	.612
Notch angle	0.99 (0.95-1.04)	.821	0.96 (0.92-1.01)	.092
Notch shape				
Type U	1.00 (reference)		1.00 (reference)	
Type A	1.40 (0.51-3.84)	.511	1.13 (0.41-3.10)	.813
NWI	0.86 (0.77-0.96)	**.006**	1.01 (0.91-1.12)	.848

[a]Bold font indicates statistical significance. ACL, anterior cruciate ligament; LFCR, lateral femoral condyle ratio; LMBA, lateral compartment meniscus-bone angle; LMCS, lateral compartment middle cartilage slope; LTS, lateral tibial slope; NWI, notch width index; RRR, relative risk ratio; TSF, tibial spine fracture.

control group but did not differ between the ACL and control groups (see Appendix Table A3). A comparison of parameters between the ACL and TSF groups indicated that the NWI was lower in the ACL group (23.7% ± 5.0% [range, 12.6%-34.2%]) than in the TSF group (26.3% ± 4.8% [range, 19.3%-40.1%]) (P = .03) and control group (27.0% ± 5.2% [range, 14.5%-43.8%]) (P = .004). Except for the NWI, none of the other parameters differed between the ACL and TSF groups.

Univariable multinomial logistic regression analysis showed that the articular LTS, bony LTS, LMCS, LMBA, and notch angle were associated with the occurrence of ACL tears or TSFs (see Appendix Table A4, available online). The alpha angle, notch shape, and NWI were associated with ACL tears but not with TSFs. In contrast, the LFCR was associated with TSFs but not with ACL tears.

Multivariable analysis included the medial tibial depth, articular LTS, LMCS, LMBA, LFCR, alpha angle, notch angle, notch shape, and NWI as independent variables. Of the articular LTS and bony LTS, only the articular LTS was included in the model because the articular LTS and bony LTS showed a correlation (Pearson r = 0.51; $P < .001$) and the articular LTS had a higher RRR on univariable analysis and exhibited better intraobserver and interobserver reliability than the bony LTS. A high articular LTS was a risk factor for both ACL tears (RRR, 1.42 [95% CI, 1.16-1.74]) and TSFs (RRR, 1.33 [95% CI, 1.10-1.62]) (Table 2). A high NWI was a protective factor against ACL tears (RRR, 0.86 [95% CI, 0.77-0.96]) but not against TSFs. The other parameters were not independently associated with the occurrence of ACL tears or TSFs on multivariable analysis.

A scatterplot of patients based on the articular LTS and NWI is shown in Figure 3. A receiver operating characteristic curve applied to the scatterplot showed an optimal cutoff value of 3.2° for the articular LTS, with a sensitivity of 86% and a specificity of 60% (area under the curve = 0.761 [95% CI, 0.687-0.825]; $P < .001$) in the comparison of the control group versus the TSF and ACL groups; an optimal cutoff value of 24% was found for the NWI, with a sensitivity of 68% and a specificity of 57% (area under the curve = 0.642 [95% CI, 0.562-0.716]; P = .003) in the comparison of the ACL group versus the TSF and control groups. The distribution of patients in the 3 groups differed according to an articular LTS of 3.2° and an NWI of 24% ($P < .001$) (Table 3). Overall, 23 (52%) of 44 patients with an articular LTS >3.2° and an NWI ≤24% had ACL tears,

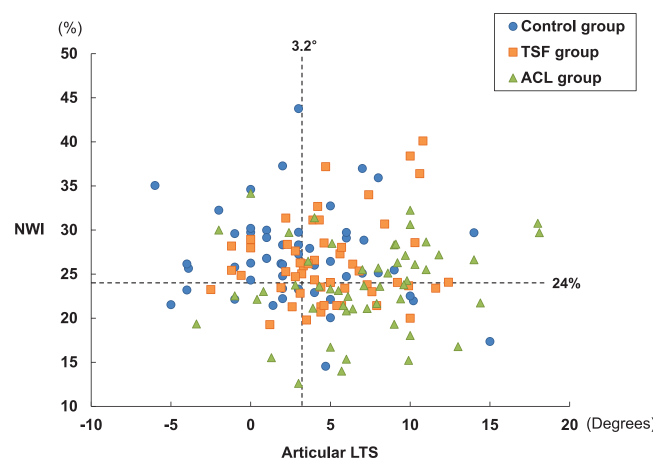

Figure 3. A scatterplot showing the patient distribution based on the articular lateral tibial slope (LTS) and notch width index (NWI). ACL, anterior cruciate ligament; TSF, tibial spine fracture.

TABLE 3
Patient Distribution Based on Articular LTS and NWI[a]

	Control (n = 53)	ACL (n = 53)	TSF (n = 53)	Total (n = 159)
Articular LTS ≤3.2° and NWI >24%	24 (60)	3 (8)	13 (33)	40 (100)
Articular LTS ≤3.2° and NWI ≤24%	8 (40)	7 (35)	5 (25)	20 (100)
Articular LTS >3.2° and NWI >24%	14 (25)	20 (36)	21 (38)	55 (100)
Articular LTS >3.2° and NWI ≤24%	7 (16)	23 (52)	14 (32)	44 (100)

[a]Data are presented as n (%). ACL, anterior cruciate ligament; LTS, lateral tibial slope; NWI, notch width index; TSF, tibial spine fracture.

whereas only 3 (8%) of 40 patients with an articular LTS ≤3.2° and an NWI >24% had ACL tears ($P < .001$).

DISCUSSION

To the best of our knowledge, this is the first study to compare morphological parameters on MRI between patients with ACL tears and those with TSFs. The strength of our study lies in the comprehensive evaluation of diverse parameters using standardized MPR images from thin-slice MRI. Another strength of our study is the inclusion of a control group, which has allowed us to determine a common risk factor for ACL tears and TSFs, which are considered equivalent injuries, and to identify the patient group with an abnormal parameter compared with the control group when that particular parameter was different between the ACL and TSF groups. Our findings suggest that a high articular LTS is a common morphological risk factor for ACL tears and TSFs and that a narrower intercondylar notch is a risk factor for ACL tears but not for TSFs.

As the posterior tibial slope is known to be associated with anterior tibial translation,[12] previous studies have evaluated it as a potential risk factor for pediatric ACL tears or TSFs.[§] However, the results have been inconsistent. Some studies suggested that an increased MTS might be a risk factor for pediatric ACL tears,[32,45] whereas others found no association.[11,15,26] Similarly, some studies found a relationship between an increased LTS and the occurrence of pediatric ACL tears,[11,15,26,35] whereas others did not.[2,18,31,45] Regarding pediatric TSFs, 3 studies evaluated the posterior tibial slope on radiography,[29,37,38] with 1 study reporting the association of MTS with the occurrence of TSFs[29] and the other 2 studies reporting the opposite result.[37,38] No studies evaluated the tibial slope on MRI in pediatric TSFs, but 1 study did in adult TSFs,[49] reporting that a high LTS was an independent risk factor for TSFs but that a high MTS was not. These conflicting results regarding the posterior tibial slope as a risk factor for ACL tears or TSFs may be attributed to differences in the measurement methods, imaging modalities (radiography vs MRI), and study populations. In the current study, the LTS was higher in the ACL and TSF groups than in the control group, but the MTS was not (Tables 1 and 2; see Appendix Table A3), which concurs with the results of the study on adult TSFs.[49] The condition of having a steeper lateral tibial plateau than a medial tibial plateau may cause an axial loading force to slide the lateral femoral condyle posteriorly off the lateral tibial plateau, with the medial tibial plateau as a pivot point.[39] We believe that excessive strain on the ACL by this external rotation of the femur could be a common risk factor for pediatric ACL tears and TSFs.

There are 2 studies that have compared the NWI between pediatric ACL tears and TSFs using radiography, yielding contradictory results.[25,37] Kocher et al[25] reported a lower NWI in the ACL group than in the TSF group. Conversely, Samora et al[37] did not detect a significant difference in the NWI among the pediatric ACL, TSF, and control groups. The intercondylar notch width or NWI on MRI has not been compared between ACL tears and TSFs; instead, studies have focused on comparisons with controls.[2,4,16,23,39,40,44,47] Certain studies have reported a narrower intercondylar notch or lower NWI in patients with ACL tears compared with controls,[16,23,39,40,47] whereas others have found no significant difference.[2,4,44] A single study comparing the NWI between adult patients with TSFs and controls reported that a low NWI was independently associated with the occurrence of TSFs.[49] The variability in results could be caused, in part, by differences in measurement planes (axial, coronal, or coronal oblique) used across studies. Studies, including the present one in which the intercondylar notch width was evaluated in the coronal oblique plane parallel to the ACL, have reported a narrower intercondylar notch in the ACL group[39,47] (Tables 1 and 2; see Appendix Table A3). We assume that among patients with risk factors for excessive ACL strain, those with a narrow intercondylar notch may experience impingement of the ACL against the notch, leading to an ACL tear, while those with a normal or wide intercondylar notch may experience TSFs instead.

TSFs usually occur at a younger age, peaking at 8 to 14 years of age,[24] compared with ACL tears, the occurrence of which peaks at 14 to 17 years of age.[8,22] Accordingly, 2 previous studies investigated whether skeletal maturity is a factor for determining the occurrence of pediatric ACL tears versus TSFs.[25,37] However, neither study found a significant difference in bone age based on knee radiography. Our study also did not identify a significant difference in bone age based on MRI between pediatric ACL tears and TSFs. Although the current study estimated the bone age using knee MRI, no significant difference in bone age

[§]References 2, 11, 15, 18, 26, 31, 32, 35, 45.

was observed between the ACL and TSF groups. Nevertheless, the correlation between bone age assessed by knee MRI and bone age evaluated using knee radiography has not been examined, and they may not necessarily be equivalent.

A previous study discovered that the pediatric ACL group had a smaller roof inclination angle than the TSF and control groups.[37] The roof inclination angle, an alpha angle on lateral knee radiography, indicates a smaller value for a steeper intercondylar notch roof. However, other studies found a larger alpha angle in the ACL group than in the control group.[5,16] In another study, the alpha angle was larger only in female patients with ACL tears than in female controls but not in male patients with ACL tears.[23] In the present study, the large alpha angle showed an association with the occurrence of ACL tears on univariable analysis; however, no independent association was found on multivariable analysis (Table 2; see Appendix Table A4).

While anatomic morphology is generally considered a nonmodifiable factor, understanding critical morphological parameters may contribute to the identification of patients at a high risk for injuries and to the adjustment of modifiable factors to mitigate such a risk. For instance, children identified as high-risk candidates may switch to lower risk sports, reduce their injury exposure, or actively participate in injury prevention programs that include neuromuscular training.[42] Furthermore, the modification of anatomic morphology may aid in injury prevention; for instance, guided growth for the correction of an elevated tibial slope in children with an open physis may improve their knee stability[19] and potentially help in preventing the occurrence of ACL tears or TSFs. Notchplasty has also been suggested by some studies to be beneficial in preventing ACL retears.[33,43] Currently, routine MRI screening for young athletes is not widespread. Nevertheless, several athletes already undergo MRI for various reasons such as diagnosing ACL tears or TSFs and identifying the cause of anterior knee pain.[36] Insights derived from research on morphological risk factors could contribute to the prevention of injuries and the reduction of reinjury rates. With the increase in accessibility to MRI and the decrease in associated costs, more patients may benefit from this knowledge.

Limitations

This study has several limitations. First, owing to the unclear mechanism of injuries in some patients, we were unable to limit the study population to patients with noncontact injuries. To analyze the effect of morphology on ACL tears or TSFs, it would have been preferable to restrict the study population to patients with noncontact injuries. Second, we analyzed measurements from MRI immediately after the injury, which may not accurately represent the preinjury state because injuries could alter knee morphology.[6] Third, the presence of ACL tears or TSFs themselves not only hindered the evaluation of several parameters such as the ACL volume and tibial spine height, which are known to be potential risk factors for ACL tears,[10,35,40] but also hampered group blinding because we could determine whether a patient had ACL tears, TSFs, or no injury on MRI and could not consequently blind ourselves from knowing which patient belonged to a certain group when conducting measurements on MRI. However, we assessed various morphological parameters for both the medial and lateral compartments of the tibiofemoral joint and for the intercondylar notch, and we expended considerable effort to ensure that our knowledge of which patients belonged to a certain group did not influence the measurements. Fourth, the sample size of our study precluded a subgroup analysis based on age, race, and sex. Previous studies have reported age- and race-related differences in knee morphological parameters[35,46] as well as varying associations between parameters and ACL tears according to sex.[23,40] Furthermore, our study groups may not have been representative of the general ACL injury population, as we demographically matched the ACL group to the TSF group to show no differences in age or sex; notably, our TSF group predominantly consisted of non-White patients and was largely male. Fifth, this study was conducted at a single center; the results of a multicenter study conducted in a different setting may differ from our findings. Sixth, bone contusions, meniscal tears, and other ligamentous injuries associated with ACL tears or TSFs were not evaluated in this study. Seventh, differences among groups were not evaluated based on their referral patterns. Lastly, our control group consisted of patients rather than true healthy knees; they were simply knees that served as a control without ACL issues.

CONCLUSION

A higher articular LTS was a common risk factor for ACL tears and TSFs. Patients with ACL tears had a narrower intercondylar notch than those with TSFs and controls. Future studies may focus on verifying whether modifying the tibial slope or femoral intercondylar notch width could reduce the risk of reinjuries in patients with ACL tears or TSFs.

AUTHORS

Chang Ho Shin, MD (Seoul National University Children's Hospital, Seoul, Republic of Korea; Seoul National University College of Medicine, Seoul, Republic of Korea); Akbar N. Syed, MD (Children's Hospital of Philadelphia, Philadelphia, Pennsylvania, USA); Morgan E. Swanson, BA (Children's Hospital of Philadelphia, Philadelphia, Pennsylvania, USA); J. Todd R. Lawrence, MD, PhD (Children's Hospital of Philadelphia, Philadelphia, Pennsylvania, USA; Perelman School of Medicine, University of Pennsylvania, Philadelphia, Pennsylvania, USA); Soroush Baghdadi, MD (University of California, Los Angeles, Los Angeles, California, USA); Aristides I. Cruz Jr, MD (Hasbro Children's Hospital, Providence, Rhode Island, USA); Henry B. Ellis Jr, MD (Scottish Rite for Children, Dallas, Texas, USA); Peter D. Fabricant, MD (Hospital for Special Surgery, New York, New York, USA); Daniel W. Green, MD (Hospital for Special Surgery, New York, New York, USA); Alicia Kerrigan, MD (Children's Hospital of Eastern Ontario, Ottawa, Ontario, Canada); Julia Kirby, MD (Austin Health, Heidelberg, Victoria, Australia); Mininder Kocher, MD (Boston Children's Hospital, Boston, Massachusetts, USA); Indranil V. Kushare, MD (Texas Children's Hospital, Houston, Texas, USA); R. Jay Lee, MD (Johns Hopkins Hospital, Baltimore, Maryland, USA); James P. MacDonald, MD (Nationwide Children's Hospital, Columbus, Ohio, USA); Scott D. McKay, MD (Texas Children's Hospital, Houston, Texas, USA); Shital N. Parikh, MD (Cincinnati Children's Hospital Medical Center, Cincinnati, Ohio, USA); Neeraj M. Patel, MD (Ann & Robert H. Lurie Children's Hospital of Chicago, Chicago, Illinois, USA); Yi-Meng Yen, MD (Boston Children's Hospital, Boston, Massachusetts, USA); Gregory A. Schmale, MD (Seattle Children's Hospital, Seattle, Washington, USA); Kevin G. Shea, MD (Lucile Packard Children's Hospital, Palo Alto, California, USA); R. Justin Mistovich, MD (Case Western Reserve University, Cleveland, Ohio, USA; University Hospitals Rainbow Babies & Children's Hospital, Cleveland, Ohio, USA); and Theodore J. Ganley, MD (Children's Hospital of Philadelphia, Philadelphia, Pennsylvania, USA; Perelman School of Medicine, University of Pennsylvania, Philadelphia, Pennsylvania, USA).

ORCID iDs

Chang Ho Shin https://orcid.org/0000-0002-4154-7964
Akbar N. Syed https://orcid.org/0009-0002-3270-7708

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