Anatomic Differences in the Sagittal Knee Joint Are Associated With ACL Injury

Results From a Skeletally Immature Korean Population

Yoon Hae Kwak,* MD, PhD, Ji-Hoon Nam,† MS, Yong-Gon Koh,‡ MD, Byoung-Kyu Park,§ MD, and Kyoung-Tak Kang,†‖ PhD

Investigation performed at Yonsei University College of Medicine, Severance Hospital, Seoul, Republic of Korea

Background: Differences in tibiofemoral articular morphology are associated with risks of anterior cruciate ligament (ACL) injury.

Purpose: To determine whether bony and cartilaginous morphological characteristics are related to ACL injury in pediatric patients and to investigate any differences according to sex.

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

Methods: A total of 200 skeletally immature Korean patients from a single institution were included in this study; 100 patients had an ACL injury, and 100 had an intact ACL. Condylar morphology and tibial slopes were evaluated and compared between the groups, and differences between sexes were evaluated in the ACL-injured group.

Results: The lateral femoral curvature was significantly greater and the lateral and medial tibial curvatures were significantly smaller in the ACL-injured group than in the intact group ($P < .01$ for all). In addition, the lateral and medial femoral curvatures as well as the lateral tibial curvature were significantly smaller in female than in male patients ($P < .01$ for all). Both the medial and lateral tibial slopes were greater in the ACL-injured versus intact group (medial slope, 5.5° vs 5.0°; lateral slope, 3.0° vs 1.3°, respectively); this difference was statistically significant for lateral tibial slope ($P = .026$). No sex-based differences were found for medial or lateral tibial slope.

Conclusion: Femoral and tibial curvatures as well as lateral tibial slope were significantly different between the ACL-injured and ACL-intact patients, and the lateral tibial curvature was significantly smaller in female than in male patients. Medial and lateral tibial slopes were not associated with a significant difference in ACL injury between male and female patients.

Keywords: Korean pediatric patients; morphometry; femoral condyle; tibial condyle; tibial slope

Pediatric and adolescent sports medicine is a subspecialty niche in orthopaedics that has shown exponential growth in the past 10 years due to new cultural trends and activity patterns among young people.[19] Anterior cruciate ligament (ACL) injury in skeletally immature patients has received particular attention.[26] The increase in such injuries is multifactorial, including increased sports participation, earlier sport specialization, year-round play, increased injury recognition, and increased use of magnetic resonance imaging (MRI).[1,2]

Normal morphological characteristics, signal characteristics, and the position and morphology of the ACL in MRI are well-described in adults.[17,18] However, interpreting diagnostic images in children requires a comprehensive understanding of normal, developmental-related changes and injuries that are unique to the immature skeleton.[11] Variations in bony morphology are thought to be associated with the risk of ACL injury.[8,9] In addition, multiple anatomic features of the tibial plateau and femoral condyle have been suggested as potential risk factors for ACL injury.[21,22] Despite the well-established role of those anatomic features in ACL injury risk, it remains unclear how they develop in pediatric patients. A previous study showed that small intercondylar notch dimensions correlate with an increased risk of ACL rupture on the femoral side.[24] Similarly, medial tibial slope is increased in pediatric populations according to a study using plain radiographs.[27] Hashemi et al[8,9] noticed differences between male and female participants in the slopes of the medial and lateral proximal aspects of the tibia in both the sagittal and coronal planes and identified those slopes as potential risk factors for ACL injury. In addition, increased posterior slope

The Orthopaedic Journal of Sports Medicine, 9(4), 2325967121994795
DOI: 10.1177/2325967121994795

causes greater anterior translation of the tibia during simple weightbearing activities, which increases strain on the ACL during substantial compressive loads.[3] However, 2 meta-analyses found opposing conclusions.[29,31] These inconsistencies could be due to differences in inclusion and exclusion criteria, imaging examination, method of diagnosis, reference axis, low participant enrollment, study type, methodological quality, and countries or origins.[32]

Wahl et al[28] showed that lateral sagittal tibiofemoral articular geometry can play a role in the development of noncontact ACL injuries. However, no previous study has evaluated tibial slope and tibiofemoral articular geometry simultaneously in the sagittal plane or found a relationship with ACL injury in pediatric patients. In addition, whether sex-based anatomic differences in the knee occur in pediatric patients has not yet been determined.

The purpose of this study was to determine whether sagittal bony morphological characteristics are associated with ACL injuries in a pediatric population. The tibiofemoral articular morphology was also compared to investigate the effect of sex. Femoral and tibial curvatures as well as the posterior tibial slope were evaluated. We hypothesized that the lateral tibiofemoral articular morphological characteristics would be different in pediatric patients with versus without ACL injury and that these differences would be sex-related.

METHODS

This study was approved by an institutional review board. A chart review identified all patients who had presented to our institution's pediatric orthopaedic clinic between 2004 and 2020 for knee pain or clinically suspected knee pathology. The inclusion criteria were skeletally immature, consecutive pediatric patients (≤18 years) and the availability of knee MRI scans of suitable quality indicating definite ACL tears. Exclusion criteria were evidence of intra-articular injuries that precluded the measurement of chondral anatomic features or concomitant injuries to other ligaments. Patients who had deformed bony structures caused by bone tumors, physeal arrest, osteochondral fracture, or patellar dislocation were also excluded from this study. A total of 100 patients with ACL injury were selected (injured group).

A case-control design was used to minimize potential confounding from variables that could be associated with both tibiofemoral morphology and ACL injury. We retrospectively selected a control group of 100 patients, matched by age and sex with the study group, who had MRI scans that showed no ACL injury (intact group). The MRI diagnoses of the intact group are listed in Table 1.

TABLE 1
MRI Diagnosis of the Intact Group

Diagnosis	n
Normal	66
Nonossifying fibroma	9
Patellar tendinopathy	4
Chondromalacia of patella	4
Osteochondroma	3
Osgood-Schlatter disease	3
Sprain of the vastus lateralis muscle	3
Discoid meniscus	3
Medial plica syndrome	1
Juvenile idiopathic arthritis	1
Hemangioma	1
Ganglion cyst	1
Bipartite patella	1
Total	100

MRI scans were acquired using a 3.0-T MRI scanner (Philips Medical System) with a 3-dimensional, proton density, volume isotropic turbo spin-echo acquisition (3D PD VISTA SPAIR) sequence, which is useful for evaluating ligaments and cartilage in the joint. Imaging was performed with 1400-ms repetition time, 33-ms echo time, 0.5-mm slice thickness, 160-mm field of view, 90° flip angle, 320 × 320 matrix, and 357 Hz/pixel bandwidth.

MRI scans were transferred in Digital Imaging and Communications in Medicine format from our institution's electronic picture archiving and communication system software (Centricity; GE Healthcare). The sagittal slices were imported into NX software (Version 11; Siemens) to measure the radius. The posterior tibial slope was measured in Mimics software (Version 17.0; Materialise). The procedures used to measure the femoral and tibial curvature (Figure 1) and posterior tibial slope (Figure 2) were consistent with those described in previous studies.[8,15] Two independent observers blinded to the participants' medical history measured the curvature and posterior tibial slope on the MRI scans. To evaluate intra- and interobserver variability, the MRI scans were remeasured >1 week after the initial measurements by the same 2 observers.

Statistical Analysis

The arithmetic means, standard deviations, and 95% CIs were calculated to describe the morphological data.

‖Address correspondence to Kyoung-Tak Kang, PhD, Department of Mechanical Engineering, Yonsei University, 50 Yonsei-ro, Seodaemun-gu, Seoul, 03722, Republic of Korea (email: tagi1024@gmail.com).

*Department of Orthopaedic Surgery, Yonsei University College of Medicine, Severance Hospital, Seoul, Republic of Korea.

†Department of Mechanical Engineering, Yonsei University, Seoul, Republic of Korea.

‡Joint Reconstruction Center, Department of Orthopaedic Surgery, Yonsei Sarang Hospital, Seoul, Republic of Korea.

§Department of Orthopaedic Surgery, Inje University Haeundae Paik Hospital, Busan, Republic of Korea.

Final revision submitted September 21, 2020; accepted November 17, 2020.

The authors declared that there are no conflicts of interest in the authorship and publication of this contribution. AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.

Ethical approval for this study was obtained from Severance Hospital, Yonsei University College of Medicine (IRB No. 4-2019-0641).

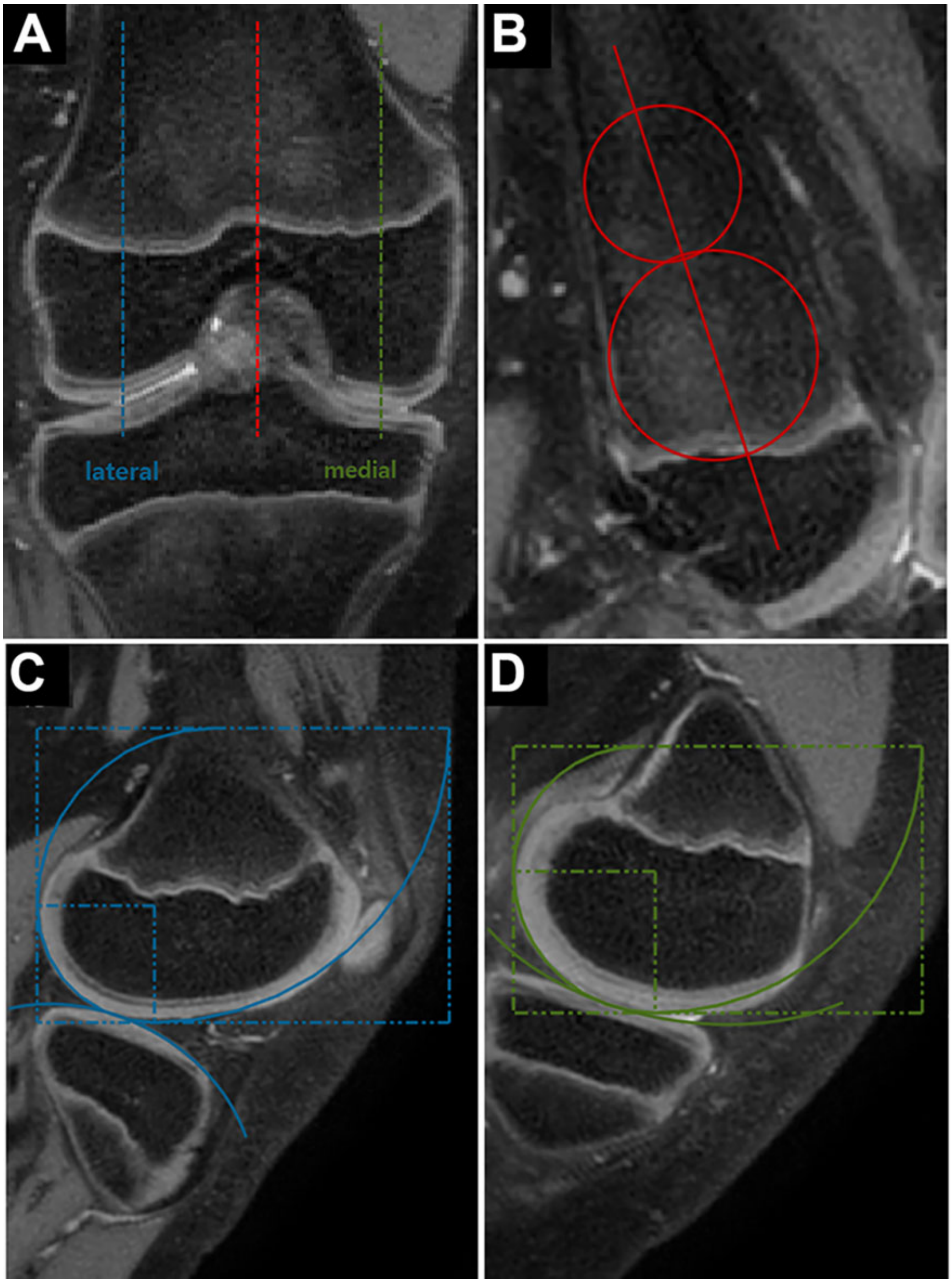

Figure 1. Measuring the femoral curvature on magnetic resonance imaging. (A) Three sagittal sections were created on the coronal plane of the femur: the middle section of the femur (dashed red line), the lateral condyle (dashed blue line), and the medial condyle (dashed green line). (B) On the sagittal section of the dashed red line in (A), the longitudinal femoral axis (solid red line) was determined by connecting the centers of 2 best-fit circles. (C) The lateral femoral curvature radii (solid blue lines) were determined using a Fibonacci spiral on the sagittal plane of the dashed blue line in (A). (D) The medial femoral curvature radii (solid green lines) were determined on the sagittal plane of the dashed green line in (A). The femoral lateral and medial anteroposterior lengths were also determined on the sagittal plane.

Statistical data were analyzed using SPSS (Version 18.0, IBM), and the Student *t* test was used to examine the significance of the differences between groups. The chi-square test was used to examine the difference in categorical data. The differences were regarded as significant when $P < .05$. A power analysis was conducted in a post hoc manner using G power 3.1. The input parameter was the tibial lateral radius of intact and injured patients. The alpha value was

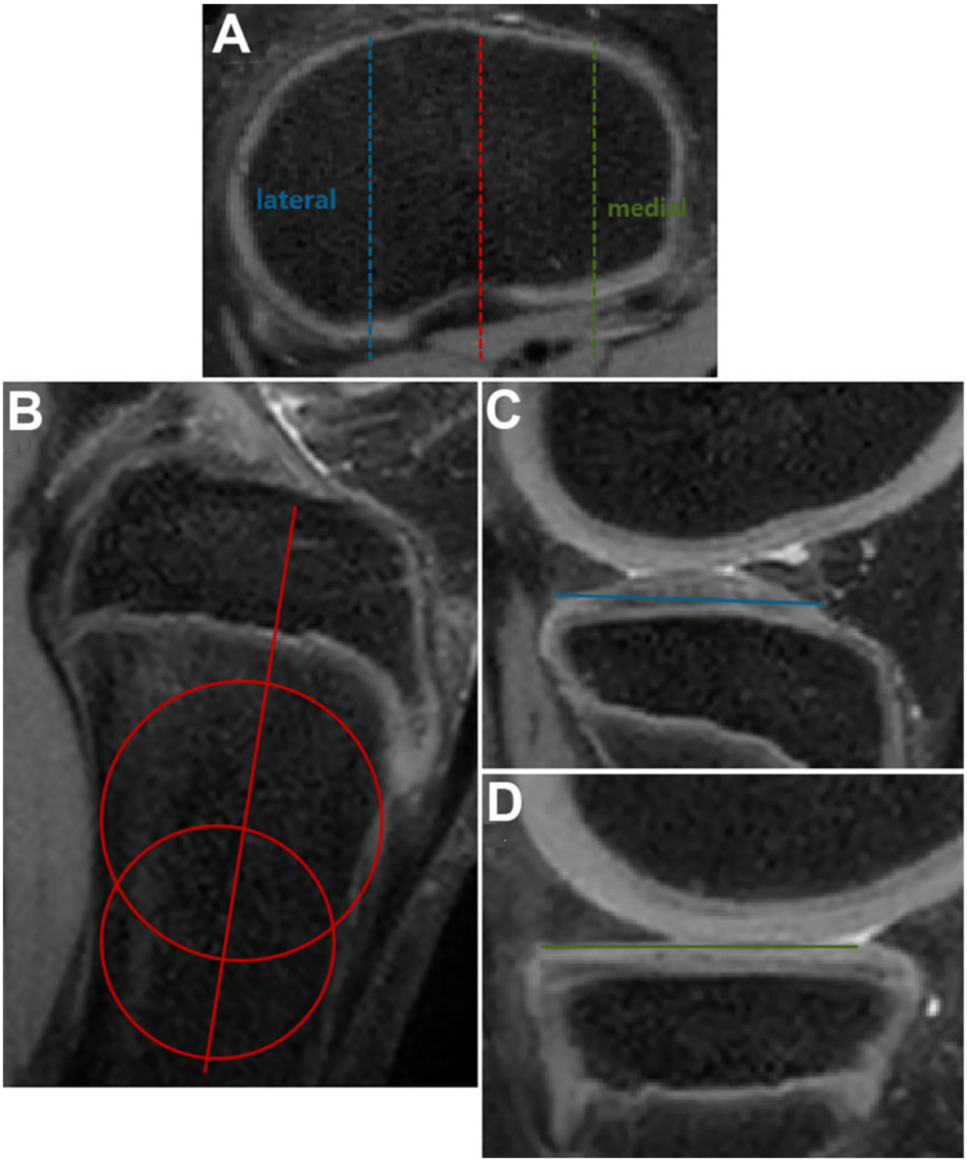

Figure 2. Measuring the tibial curvature on magnetic resonance imaging. (A) Three sagittal sections were created on the proximal transverse plane of the tibia: the middle section of the transverse tibia (dashed red line), the lateral tibial plateau (dashed blue line), and the medial tibial plateau (dashed green line). (B) On the sagittal section of the dashed red line in (A), the longitudinal tibial axis (solid red line) was determined by connecting the centers of 2 best-fit circles. (C) The lateral posterior tibial slope was determined by connecting the anterior aspect of the anterior horn and the posterior aspect of the posterior horn of the meniscus on the sagittal plane of the dashed blue line in (A). (D) The medial posterior tibial slope was determined by connecting the posterior aspect of the anterior horn and the posterior aspect of the posterior horn of the meniscus on the sagittal plane of the dashed green line in (A). The tibial lateral and medial anteroposterior lengths were also determined on the sagittal plane. The posterior tibial angle was determined as the angle between the posterior tibial slope line and longitudinal tibial axis.

.05, and the statistical power was 90.6%. The target power of previous studies was 80%,[12,15] making the power value of this study higher than that in previous studies.

RESULTS

All study patients were aged between 3 and 18 years, and 76% were male. No significant differences were noted in age or sex distribution between the intact and injured groups (Table 2). The intra- and interobserver reliabilities of the MRI measurements were 0.87 and 0.92, respectively, as calculated using the intraclass correlation method. This indicated excellent reliability.

Table 3 shows the femoral and tibial AP lengths and curvatures in the intact and injured groups. The lateral and medial AP lengths of the femur and tibia did not differ significantly between the groups; however, there were significant

TABLE 2
Patient Age and Sex Distribution Between the Intact and Injured Groups[a]

Parameter	All (N = 200)	Intact ACL (n = 100)	Injured ACL (n = 100)	*P* Value
Age, y, mean ± SD (range)	14.4 ± 3.7 (3-18)	14.4 ± 3.6 (3-18)	14.5 ± 3.8 (3-18)	.66
Sex, female/male, n	52/148	25/75	27/73	.78

[a]ACL, anterior cruciate ligament.

TABLE 3
Anteroposterior Lengths and Sagittal Curvatures Between the Intact and Injured Groups[a]

Parameter	All (N = 200)	Intact ACL (n = 100)	Injured ACL (n = 100)	*P* Value
Anteroposterior length, mm				
Femur: lateral	65.1 ± 8.1 (32.2-78.5)	64.4 ± 8.1 (32.2-77.8)	65.8 ± 8.2 (34.4-78.5)	.24
Femur: medial	56.3 ± 7.6 (31.1-70.1)	55.5 ± 7.9 (31.5-70.1)	57.1 ± 7.2 (31.1-68.4)	.14
Tibia: lateral	43.4 ± 6.7 (23.8-56.7)	43.5 ± 7.1 (25.9-55.6)	43.4 ± 6.4 (23.8-56.7)	.92
Tibia: medial	52.0 ± 7.7 (28.7-64.7)	51.4 ± 7.7 (30.9-62.6)	52.5 ± 7.7 (28.7-64.7)	.31
Sagittal curvature, mm				
Femur: lateral	22.7 ± 3.6 (13.3-30.6)	22.0 ± 3.5 (13.3-29.8)	23.4 ± 3.5 (15.2-30.6)	**<.01**
Femur: medial	24.9 ± 4.4 (11.7-35.7)	24.4 ± 4.5 (14.0-35.7)	25.3 ± 4.2 (11.7-34.9)	.14
Tibia: lateral	41.3 ± 8.6 (19.3-67.5)	43.1 ± 8.5 (20.9-63.5)	39.6 ± 8.4 (19.3-67.5)	**<.01**
Tibia: medial	50.9 ± 12.2 (27.6-89.0)	57.4 ± 10.7 (27.6-89.0)	44.9 ± 10.4 (28.3-74.2)	**<.01**

[a]Data are reported as mean ± SD (range). Bolded *P* values indicate statistically significant difference between the intact and injured groups ($P < .05$). ACL, anterior cruciate ligament.

TABLE 4
Anteroposterior Lengths and Sagittal Curvatures Between Female and Male Patients[a]

Parameter	All (N = 200)	Female (n = 51)	Male (n = 149)	*P* Value
Anteroposterior length, mm				
Femur: lateral	65.1 ± 8.1 (32.2-78.5)	60.7 ± 5.7 (44.6-69.3)	66.7 ± 8.3 (32.2-78.5)	**<.01**
Femur: medial	56.3 ± 7.6 (31.1-70.1)	52.8 ± 7.9 (31.1-70.1)	57.6 ± 7.9 (31.1-70.1)	**<.01**
Tibia: lateral	43.4 ± 6.7 (23.8-56.7)	38.8 ± 4.6 (27.5-47.1)	45.1 ± 6.6 (23.8-56.7)	**<.01**
Tibia: medial	52.0 ± 7.7 (28.7-64.7)	46.5 ± 4.6 (34.5-53.9)	54.0 ± 7.6 (28.7-64.7)	**<.01**
Sagittal curvature, mm				
Femur: lateral	22.7 ± 3.6 (13.3-30.6)	21.2 ± 3.0 (13.3-28.5)	23.2 ± 3.6 (13.3-30.6)	**<.01**
Femur: medial	24.9 ± 4.4 (11.7-35.7)	23.5 ± 3.4 (15.2-32.7)	25.4 ± 4.6 (11.7-35.7)	**<.01**
Tibia: lateral	41.3 ± 8.6 (19.3-67.5)	37.5 ± 6.7 (24.2-54.8)	42.6 ± 8.8 (19.3-67.5)	**<.01**
Tibia: medial	50.9 ± 12.2 (27.6-89.0)	57.4 ± 14.4 (30.0-89.0)	50.2 ± 11.3 (27.6-82.9)	.18

[a]Data are reported as mean ± SD (range). Bolded *P* values indicate statistically significant difference between female and male patients ($P < .05$).

differences in the curvature of the lateral femoral condyle and the medial and lateral tibial plateaus ($P < .01$ for all) (Table 3).

When results were compared by sex, the medial and lateral anteroposterior (AP) lengths of the femur and tibia were significantly greater in male than in female patients ($P < .01$) (Table 4). The medial and lateral curvature in the femur and the lateral curvature in the tibia were also significantly greater in male than in female patients ($P < .01$). However, the tibial medial curvature did not differ by sex (Table 4).

The lateral tibial slope was significantly greater in the injured group versus the intact group ($3.0^\circ \pm 5.6^\circ$ vs $1.3^\circ \pm 4.9^\circ$; $P = .026$). The medial tibial slope did not differ significantly between the groups (Table 5). When results were compared by sex, the lateral and medial tibial slopes did not differ significantly (Table 6).

DISCUSSION

The most important finding of this study is that significant morphological differences were seen between lateral femoral and tibial curvature and lateral tibial slope between patients with and without ACL injuries. In addition, sex differences were found in the femoral and tibial curvatures, except for the medial tibial curvature. The medial femoral curvature and medial posterior tibial slope did not differ between patients with and without ACL injuries, and no sex difference was found in the medial and lateral posterior tibial slopes.

The prevalence of ACL injuries emphasizes the need for further investigation of the factors associated with these injuries.[28] Previous studies found bony morphology to be a risk factor for ACL injury.[6,27,28] The femur has a nearly

TABLE 5
Posterior Tibial Slope Between the Intact and Injured Groups[a]

Parameter	All (N = 200)	Intact ACL (n = 100)	Injured ACL (n = 100)	*P* Value
Medial tibial slope, deg	5.3 ± 5.6 (–14.0 to 23.3)	5.0 ± 5.4 (–14.0 to 17.5)	5.5 ± 5.7 (–12.5 to 23.3)	.50
Lateral tibial slope, deg	2.1 ± 5.3 (–10.4 to 21.7)	1.3 ± 4.9 (–9.0 to 14.9)	3.0 ± 5.6 (–10.4 to 21.7)	**.026**

[a]Data are reported as mean ± SD (range). Bolded *P* value indicates statistically significant difference between intact and injured groups ($P < .05$). ACL, anterior cruciate ligament.

TABLE 6
Posterior Tibial Slope Between Female and Male Patients[a]

Parameter	All (N = 200)	Female (n = 51)	Male (n = 149)	*P* Value
Medial tibial slope, deg	5.3 ± 5.6 (–14.0 to 23.3)	5.8 ± 5.2 (–12.5 to 23.3)	5.1 ± 5.7 (–14.0 to 18.0)	.36
Lateral tibial slope, deg	2.1 ± 5.3 (–10.4 to 21.7)	1.6 ± 5.5 (–6.1 to 21.7)	2.3 ± 5.3 (–10.4 to 15.7)	.43

[a]Data are reported as mean ± SD (range).

spherical geometry at its contact point with the tibia.[20] The morphology of the lateral tibial plateau changes substantially from its medial aspect at the tibial spine to its lateral edge because the medial and lateral tibial plateaus are slightly concave and convex, respectively.[16] Wahl et al[28] showed that lateral knee geometry characterized by a smaller tibial plateau length relative to the femur and more convex articulating surfaces of the proximal aspect of the tibia and the distal aspect of the femur is more common in patients with ACL injuries than in patients without such injuries. However, participants in previous studies were adults, and only the lateral tibiofemoral joint was investigated.[28] We investigated the medial and lateral curvatures of the femur and tibia in pediatric patients with and without ACL injuries. Our results showed that all factors except femoral medial curvature differed significantly between patients with and without ACL injuries, which was consistent with the results of a previous study.[28] However, we found no significant difference in AP length between patients with and without ACL injuries, which differed from the results of that study.[28] Those morphometric characteristics are associated with genetic, environmental, and cultural conditions, as well as lifestyle, health, and functional status, which makes it difficult to provide a standard interpretation of their values.[14]

Anthropometric sex differences that represent potential risk factors for ACL injury have been widely investigated.[24,28] It is likely that noncontact ACL injuries are caused by a combination of variables.[24,28] We found sex-related differences in AP length and all curvatures except medial tibial curvature. The values from female patients were significantly smaller than those from male patients, which is consistent with previously published results.[5,13,28,30] Our measurements for AP length and curvature were smaller than in previous studies because we tested pediatric patients, whereas the previous studies examined adults. In addition, the tibial plateau AP length relative to the femoral AP length differed significantly between male and female participants, with the female tibial lateral plateau being relatively shorter and more convex.

Most previous studies showed an increased risk of ACL tears in adults with increased tibial slope.[6,21,23,27] An increase in athletic activity and increased recognition of the injury have led to an increase in the number of ACL injuries diagnosed in pediatric patients. A previous study compared the posterior tibial slope on radiographs between 32 ACL-injured participants with open physes and controls and found a moderate association between increased posterior tibial slope and ACL injury in pediatric patients.[27] Although that study provided useful initial data from this unique population, those researchers measured the medial and lateral tibial plateaus using radiographs, thereby potentially ignoring asymmetry in the medial and lateral aspects of the tibia. For many reasons, MRI is considered superior to radiography for measuring the posterior slope in pediatric patients.[6]

Dare et al[6] reported that the lateral posterior tibial slope in patients without an ACL injury was 3.38° ± 1.70° and the medial posterior tibial slope was 5.08° ± 2.25°, whereas lateral posterior tibial slope in patients with an ACL injury was 5.66° ± 2.38° and medial posterior tibial slope was 5.39° ± 2.22°. In our results, the lateral posterior tibial slope in patients without an ACL injury was 1.3° ± 4.9° and the medial posterior tibial slope was 5.0° ± 5.4°, whereas the lateral posterior tibial slope in patients with an ACL injury was 3.0° ± 5.6° and the medial posterior tibial slope was 5.5° ± 5.7°. Thus, our study showed that the lateral posterior tibial slope in the ACL-injured patient group was significantly greater than that in the uninjured patient group. The medial posterior tibial slope was also greater but without significance. Those results are similar to those reported by Dare et al.[6] Another previous study suggested that increased lateral posterior tibial slope relative to medial posterior tibial slope produced net internal rotation of the tibia relative to the femur, which increased ACL strain values.[21] Despite the increasing interest in tibial slope and its association with ACL injury, the level of risk posed by this anatomic factor remains unclear.[6] We found no significant difference in medial posterior tibial slope between the ACL injured and uninjured groups, which differs from the results of a similar study in pediatric patients that found an increase in the medial posterior tibial slope in the ACL-injured group compared with the uninjured group.[27] However, many other previous studies have shown that the lateral posterior tibial slope is a risk factor for ACL injury.[6,10,21,25,32] A sex-related difference in bony morphology was hypothesized because many previous studies found that female participants had a greater propensity for ACL injuries than male participants.[4,27] However, we did not find such a difference in posterior tibial slope in our Korean pediatric population.

In terms of clinical relevance, the convex shape of the lateral aspect of the tibial plateau has been recognized as important, but few studies have attempted to correlate the degree of convexity with the risk of ACL injury. Nonetheless, a lateral tibiofemoral articular surface characterized by a shorter and more convex tibial plateau relative to the femur and by a smaller and more convex distal femoral surface could render the knee joint more susceptible to ACL injury in a Korean population. Although some studies suggested that decreasing the tibial slope could benefit ACL-deficient knees, tibial plateau geometry is largely nonmodifiable.[7]

The findings of this and previous studies are important for evaluating the strain on the ACL through simulated weightbearing with varying degrees of posterior slope. Participants with an increased tibial slope who participate in high-risk activities should perhaps consider prophylactic precautions. In any case, ACL injury-prevention programs should focus on minimizing the loads transmitted to the knee joint.[6]

Our study had several limitations. First, only Korean pediatric patients were examined. Future investigations should include other Asian-Pacific populations to establish a general database in this region. Second, patients were matched for age and sex, but they were not matched for height, weight, or activity level. The absence of this information could confound our data. Third, we attempted to standardize our ACL-injured and uninjured groups to eliminate bias caused by differences in activity level, but we could not eliminate all differences. Fourth, the differences associated with age were not considered because the sample was not large enough. Also, ACL injuries were rare in young children, and age was unevenly distributed. Fifth, the design of this study was retrospective, although it would be difficult and costly to image and follow uninjured participants prospectively in anticipation of ACL injuries.

CONCLUSION

This study compared sagittal tibiofemoral joint morphology between Korean pediatric patients with and without ACL injuries and considered sex-related differences. The femoral and tibial curvature as well as lateral tibial slope showed significant difference between the injured and intact ACL groups. The medial and lateral tibial slopes were not associated with the incidence of ACL injury between sexes, but the lateral tibial curvature was significantly smaller in female patients. The differences found in tibiofemoral joint morphology could contribute to the risk of graft tears and outcomes from ACL reconstruction, but comparative clinical studies are required to support that possibility.

REFERENCES

1. Arbes S, Resinger C, Vecsei V, Nau T. The functional outcome of total tears of the anterior cruciate ligament (ACL) in the skeletally immature patient. *Int Orthop*. 2007;31(4):471-475.
2. Bollen SR, Scott BW. Rupture of the anterior cruciate ligament—a quiet epidemic? *Injury*. 1996;27(6):407-409.
3. Brandon ML, Haynes PT, Bonamo JR, et al. The association between posterior-inferior tibial slope and anterior cruciate ligament insufficiency. *Arthroscopy*. 2006;22(8):894-899.
4. Charlton WP, St John TA, Ciccotti MG, Harrison N, Schweitzer M. Differences in femoral notch anatomy between men and women: a magnetic resonance imaging study. *Am J Sports Med*. 2002;30(3): 329-333.
5. Cheng FB, Ji XF, Zheng WX, et al. Use of anthropometric data from the medial tibial and femoral condyles to design unicondylar knee prostheses in the Chinese population. *Knee Surg Sports Traumatol Arthrosc*. 2010;18(3):352-358.
6. Dare DM, Fabricant PD, McCarthy MM, et al. Increased lateral tibial slope is a risk factor for pediatric anterior cruciate ligament injury: an MRI-based case-control study of 152 patients. *Am J Sports Med*. 2015;43(7):1632-1639.
7. Giffin JR, Vogrin TM, Zantop T, Woo SL, Harner CD. Effects of increasing tibial slope on the biomechanics of the knee. *Am J Sports Med*. 2004;32(2):376-382.
8. Hashemi J, Chandrashekar N, Gill B, et al. The geometry of the tibial plateau and its influence on the biomechanics of the tibiofemoral joint. *J Bone Joint Surg Am*. 2008;90(12):2724-2734.
9. 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.
10. Hendrix ST, Barrett AM, Chrea B, et al. Relationship between posterior-inferior tibial slope and bilateral noncontact ACL injury. *Orthopedics*. 2017;40(1):e136-e140.
11. Ho-Fung VM, Jaimes C, Jaramillo D. MR imaging of ACL injuries in pediatric and adolescent patients. *Clin Sports Med*. 2011;30(4): 707-726.
12. Hoshino Y, Kuroda R, Nishizawa Y, et al. Stress distribution is deviated around the aperture of the femoral tunnel in the anatomic anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2018;26(4):1145-1151.
13. Koh YG, Nam JH, Chung HS, et al. Gender difference exists in sagittal curvature of the distal femoral condyle morphology for osteoarthritic population. *Knee Surg Sports Traumatol Arthrosc*. 2020;28(12): 3740-3746.
14. Koh YG, Nam JH, Chung HS, et al. Gender differences in morphology exist in posterior condylar offsets of the knee in Korean population. *Knee Surg Sports Traumatol Arthrosc*. 2018;27(5):1628-1634.
15. Krych AJ, Johnson NR, Mohan R, et al. Partial meniscectomy provides no benefit for symptomatic degenerative medial meniscus posterior root tears. *Knee Surg Sports Traumatol Arthrosc*. 2018;26(4): 1117-1122.
16. Kujala UM, Nelimarkka O, Koskinen SK. Relationship between the pivot shift and the configuration of the lateral tibial plateau. *Arch Orthop Trauma Surg*. 1992;111(4):228-229.
17. Moore SL. Imaging the anterior cruciate ligament. *Orthop Clin North Am*. 2002;33(4):663-674.

18. Roberts CC, Towers JD, Spangehl MJ, Carrino JA, Morrison WB. Advanced MR imaging of the cruciate ligaments. *Radiol Clin North Am*. 2007;45(6):1003-1016.
19. Schub D, Saluan P. Anterior cruciate ligament injuries in the young athlete: evaluation and treatment. *Sports Med Arthrosc Rev*. 2011; 19(1):34-43.
20. Siebold R, Axe J, Irrgang JJ, et al. A computerized analysis of femoral condyle radii in ACL intact and contralateral ACL reconstructed knees using 3D CT. *Knee Surg Sports Traumatol Arthrosc*. 2010;18(1):26-31.
21. Simon RA, Everhart JS, Nagaraja HN, Chaudhari AM. A case-control study of anterior cruciate ligament volume, tibial plateau slopes and intercondylar notch dimensions in ACL-injured knees. *J Biomech*. 2010;43(9):1702-1707.
22. 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.
23. Sonnery-Cottet B, Archbold P, Cucurulo T, et al. The influence of the tibial slope and the size of the intercondylar notch on rupture of the anterior cruciate ligament. *J Bone Joint Surg Br*. 2011;93(11):1475-1478.
24. Souryal TO, Freeman TR. Intercondylar notch size and anterior cruciate ligament injuries in athletes: a prospective study. *Am J Sports Med*. 1993;21(4):535-539.
25. 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.
26. Trentacosta N, Pace JL, Metzger M, et al. Biomechanical evaluation of pediatric anterior cruciate ligament (ACL) reconstruction techniques with and without the anterolateral ligament (ALL). *J Pediatr Orthop*. 2020;40(1):8-16.
27. Vyas S, van Eck CF, Vyas N, Fu FH, Otsuka NY. Increased medial tibial slope in teenage pediatric population with open physes and anterior cruciate ligament injuries. *Knee Surg Sports Traumatol Arthrosc*. 2011;19(3):372-377.
28. Wahl CJ, Westermann RW, Blaisdell GY, Cizik AM. An association of lateral knee sagittal anatomic factors with non-contact ACL injury: sex or geometry? *J Bone Joint Surg Am*. 2012;94(3):217-226.
29. Wordeman SC, Quatman CE, Kaeding CC, Hewett TE. In vivo evidence for tibial plateau slope as a risk factor for anterior cruciate ligament injury: a systematic review and meta-analysis. *Am J Sports Med*. 2012;40(7):1673-1681.
30. Yue B, Varadarajan KM, Ai S, et al. Gender differences in the knees of Chinese population. *Knee Surg Sports Traumatol Arthrosc*. 2011; 19(1):80-88.
31. Zeng C, Cheng L, Wei J, et al. The influence of the tibial plateau slopes on injury of the anterior cruciate ligament: a meta-analysis. *Knee Surg Sports Traumatol Arthrosc*. 2014;22(1):53-65.
32. Zeng C, Yang T, Wu S, et al. Is posterior tibial slope associated with noncontact anterior cruciate ligament injury? *Knee Surg Sports Traumatol Arthrosc*. 2016;24(3):830-837.