Risk of noncontact anterior cruciate ligament injuries is not associated with slope and concavity of the tibial plateau in recreational alpine skiers: a magnetic resonance imaging–based case-control study of 121 patients

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Risk of Noncontact Anterior Cruciate Ligament Injuries Is Not Associated With Slope and Concavity of the Tibial Plateau in Recreational Alpine Skiers

A Magnetic Resonance Imaging–Based Case-Control Study of 121 Patients

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Background: Anatomic features of the tibial plateau (ie, posterior slope and medial concavity) have been associated with an increased risk of anterior cruciate ligament (ACL) injuries. However, it remains unclear whether these findings translate to ACL injuries sustained during recreational alpine skiing.

Purpose: To investigate the association in recreational alpine skiers between prominent morphological features of the tibial plateau (slope and concavity) and the risk of sustaining an ACL injury during a noncontact incident.

Study Design: Case-control study; Level of evidence, 3.

Methods: Magnetic resonance imaging data of 121 recreational alpine skiers (74 female, 47 male) after a noncontact knee injury were used for this study. Of these patients, 80 (71% female [n = 57]) had a complete unilateral ACL tear (rupture group), and 41 (41% female [n = 17]) had no indications of an ACL injury (intact group). Two blinded independent examiners measured the slopes of the tibial plateau in the sagittal and coronal planes along with the maximum depth of the medial tibial plateau. Measurements were compared between sexes and between groups using *t* tests. Logistic regression was used to assess the associations between quantified anatomic indices and the risk of ACL injuries.

Results: Within 121 study patients, female skiers had greater odds of an ACL tear compared with male skiers (odds ratio, 3.5; 95% CI, 1.6-7.8; $P < .001$). Female skiers were more likely to have a greater lateral tibial slope (LTS) ($P = .02$) and medial tibial slope (MTS) ($P = .02$) with a shallower medial tibial depth (MTD) ($P = .02$) compared with male skiers. No differences between sexes were observed in the coronal tibial slope (CTS) ($P = .97$). Male and female skiers as a combined group showed no associations between quantified anatomic indices and the risk of sustaining an ACL tear ($P > .10$). Likewise, no significant differences were observed between the intact versus rupture group in any of the quantified anatomic indices ($P > .10$). Similar findings were observed when the analyses were repeated on male and female skiers separately.

Conclusion: Despite differences between sexes in knee anatomy and the injury risk, the sagittal and coronal slopes (LTS, MTS, CTS), as well as the concavity of the medial tibial plateau (MTD), were not associated with the risk of an ACL tear during a noncontact injury among recreational alpine skiers.

Keywords: anterior cruciate ligament; injury; tibial plateau geometry; recreational skiing

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The anterior cruciate ligament (ACL) is the most frequently injured ligament of the knee, primarily as a result of sports participation.[25] Noncontact injuries (without a direct blow to the knee joint) account for more than 70% of all ACL injuries, occurring during pivot cuts and landing maneuvers.[4,16,26] In addition to pain, lowered activity levels, and a substantial financial burden,[5,19,33] ACL injuries increase the risk of early-onset posttraumatic osteoarthritis.[31,32] Therefore, substantial interest has been developed to identify intrinsic and extrinsic risk factors associated with ACL injuries to better profile “at-risk”

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patients who then can be targeted with proper preventative interventions.[39]

Among identified risk factors, morphological characteristics of the tibiofemoral joint and their associations with the risk of ACL injuries are at the center of attention.[**] In particular, the slope of the tibial plateau in the sagittal and coronal planes,[††] along with the concavity of the medial tibial plateau,[7,18] seems to affect tibiofemoral joint biomechanics, ACL loading, and the injury risk, as shown in multiple studies. On the posterior tibial slope, an impulsive compression force (ie, increased vertical ground-reaction force) during landing generates an anterior shear force.[15] A greater posterior tibial slope increases this anterior tibial shear force,[34] anterior tibial acceleration and translation,[24,30] and ACL strain[24,30] during jump landing activities.

Previous studies have mainly investigated whether the tibial plateau shape influences the risk of an ACL injury in sports involving jump landing activities (ie, volleyball, basketball, soccer, and football).[6,7,30,34] However, little is known about how these anatomic factors affect the ACL injury risk among recreational skiers, an important concept as this population is exposed to a considerable risk for an ACL tear.[12,45] In contrast, tears occur primarily during events leading to extreme multiplanar rotations in the coronal and axial planes and knee hyperflexion in the absence of a landing-induced impulsive compression force.[13,23,27,36] These substantial differences in noncontact injuries raise doubts as to whether established anatomic features of the tibial plateau and the risk of an ACL injury are relevant to recreational alpine skiers, in whom no substantial jump landing activities are involved.

Therefore, the current study aimed to assess prominent morphological characteristics of the tibial plateau (slope and concavity) and the risk of sustaining an ACL injury during a noncontact incidence among recreational alpine skiers. We hypothesized that the risk of an ACL injury in recreational alpine skiing is not affected by the magnitude of (1) the lateral tibial slope (LTS), (2) the medial tibial slope (MTS), (3) the coronal tibial slope (CTS), or (4) the medial tibial depth (MTD) as a measure of medial tibial plateau concavity.

METHODS

We conducted this study with a retrospective cohort. This study was approved by the institutional review board of our hospital (University Hospital Basel; ID 191/11). On the basis of a priori sample size estimation, we selected a total of 121 patients (mean ± standard error [SE] age, 39.0 ± 12.3 years; 61% female [n = 74]) who sustained a noncontact knee injury during recreational alpine skiing. The patients were admitted to the Hospital Oberengadin emergency room between December 2012 and March 2013. All patients with a noncontact knee injury were included in this study. A noncontact knee injury was defined as one that occurred during an accident or an injurious event without a direct blow to the knee.[1,2,20] None of the patients studied were elite competitive skiers. We excluded patients who sustained a contact knee injury, had a bilateral noncontact knee injury, or had a history of knee injuries or associated bone injuries. All patients were evaluated for an ACL tear using magnetic resonance imaging (MRI) and divided into a rupture group, consisting of those with a complete ACL tear as a result of a noncontact knee injury (n = 80; 71% female [n = 57]), and an intact group, consisting of those with an intact ACL (n = 41; 41% female [n = 17]).

Magnetic Resonance Imaging

All injured knees underwent MRI using an Achieva 1.5-T MRI system (Philips Medical Systems) with dedicated surface multichannel knee coils. MRI data in the sagittal plane were acquired 3-dimensionally with T1-weighted fast field echo scans with a slice thickness of 1.4 mm and a bandwidth of 244.14 Hz/pixel. The patients were positioned supine with their legs extended in a neutral position and the patella facing up. The index knee was placed in a knee extremity coil and then scanned in a 3-plane localizer and the axial scout mode. Scans in the sagittal and coronal planes were obtained perpendicular to a line tangential to the posterior femoral condyles and parallel to the femoral diaphysis in the coronal scout mode, respectively.

Anatomic Index Measurements

We measured the posterior slope of the tibial plateau across both the medial (MTS) and lateral (LTS) compartments on MRI according to the techniques described by Hudek et al.[21] Briefly, the proximal tibial anatomic axis was established by connecting the centers of 2 circles within the proximal tibial diaphysis (Figure 1A). The

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[**] References 3, 7, 8, 10, 11, 15, 18, 20, 30, 37, 38, 40, 42, 43.

[††] References 6, 8, 10, 11, 15, 18, 20, 30, 38, 40, 43.

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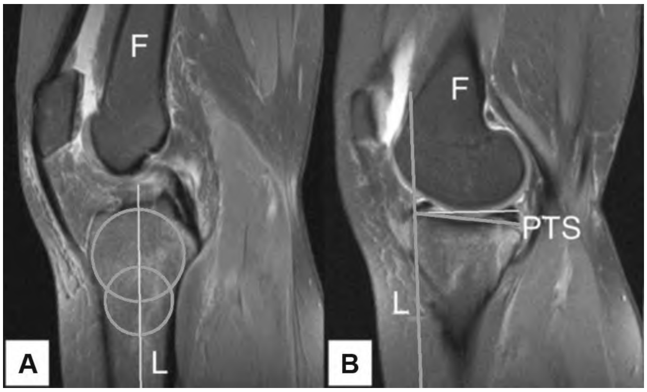

Figure 1. Techniques used to (A) establish the longitudinal axis of the proximal tibia (L) and (B) measure the posterior tibial slope (PTS) in the sagittal plane with respect to the longitudinal axis of the proximal tibia (L). F, femur.

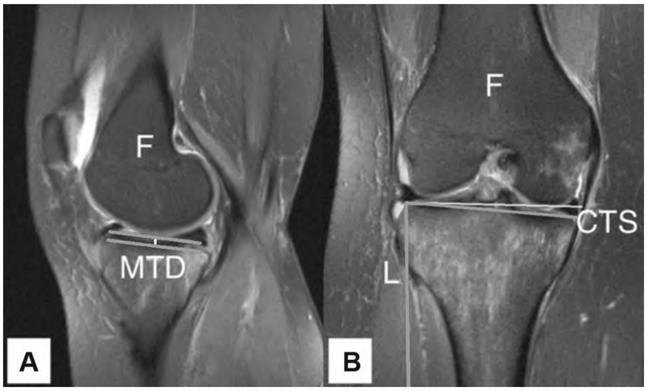

Figure 2. Techniques used to measure the (A) medial tibial depth (MTD) and (B) coronal tibial slope (CTS). F, femur; L, longitudinal axis of the proximal tibia.

posterior slope of the tibial plateau across each compartment was measured as the angle between a line connecting the peak points on the anterior and posterior aspects of the plateau and a line perpendicular to the longitudinal axis (Figure 1B). The inferiorly directed slope toward the posterior aspect of the tibial plateau in the sagittal plane was considered a positive slope.

Moreover, the coronal slope of the tibial plateau (CTS) was measured as the angle between a line connecting the peak points of the medial and lateral tibial plateaus and a line perpendicular to the proximal tibial anatomic axis in the coronal plane (Figure 2B).[6,18] The inferiorly directed slope toward the medial tibial plateau in the coronal plane was designated as a positive slope. We quantified the maximum depth of the medial tibial plateau by establishing a line connecting the superior and inferior crests of the tibial plateau in the same plane on which the MTS was measured. The MTD was defined as the perpendicular distance between this line and a parallel line drawn tangent to the lowest point of concavity in the sagittal plane (Figure 2A).[17,18] Measurements were performed by 2 independent investigators (F.B., J.F.) who were well trained for these specific measurements. The mean of both independent measurements was used for final analysis. Measurements were taken using iSite Enterprise (Philips Medical Systems) and reported in millimeters or degrees. The resolution of measurements with this software is high, with a distance accuracy of 0.1 mm and a degree accuracy of 0.1°.[14]

Statistical Analysis

A priori power calculation was used to estimate the required sample size. Previously reported anatomic data[6,8,18,41,43] were used to calculate the corresponding effect sizes for MTS (effect size = 0.63), LTS (effect size = 1.09), CTS (effect size = 0.56), and MTD (effect size = 0.72).[6,17,18,21] A priori power analysis with $\alpha = .05$ and $\beta = .80$ indicated a minimum sample size of 77 in the rupture group and a minimum sample size of 39 in the intact (control) group. As mentioned earlier, a total of 121 (80 rupture and 41 intact) patients were included in this study to ensure a minimum power of 80% to detect the differences in all mentioned anatomic indices between patients in the rupture and intact groups.

Intraclass correlation coefficients (ICCs) and root mean square errors (RMSEs) were computed to estimate the variability in measurements between the 2 independent investigators and as a surrogate measure to gauge reliability. A Shapiro-Wilk normality test was performed to verify whether the data met the assumption of a parametric test. All variables were normally distributed ($P > .20$). Age, sex distribution (percentage of female patients), and all quantified anatomic indices were compared between the rupture and intact groups using independent-samples *t* tests for continuous variables and chi-square tests for dichotomous variables. Logistic regression assessed the isolated effect of age and sex on the risk of sustaining an ACL tear. In case of significant age and/or sex effects, the analyses were adjusted for age and repeated for each sex independently. We compared subgroups between and within male and female patients using univariate analysis of variance with a post hoc Tukey-Kramer honestly significant difference to correct for multiple comparisons. Statistical analyses were performed using a standard statistical software package (JMP version 10; SAS Institute). Data are reported as mean ± SE, with $P \leq .05$ considered statistically significant.

RESULTS

Between-investigator reliability for anatomic index measurements was excellent for all quantified anatomic indices, showing high ICC and minimal RMSE values (LTS: ICC = 0.98, RMSE = 0.3°; MTS: ICC = 0.99, RMSE = 0.4°; CTS: ICC = 0.98, RMSE = 0.4°; MTD: ICC = 0.99, RMSE = 0.1 mm). The 2 study groups differed in age and sex composition. The rupture group was older by 8.6 ± 2.2 years ($P < .001$) and contained more female patients by 30% (n = 40; $P = .0015$) than the intact group. Female patients were more likely to sustain an ACL tear during a noncontact injury compared with male patients (odds ratio [OR], 3.5; 95% CI, 1.6-

TABLE 1
Quantified Anatomic Indices of the Tibial Plateau and Their Between-Group and Between-Sex Differences[a]

	All Patients (N = 121)		Female Patients (n = 74)		Male Patients (n = 47)		Difference (Male vs Female)		
Anatomic Index	Mean ± SE	95% CI	Mean ± SE	95% CI	Mean ± SE	95% CI	Mean ± SE	95% CI	*P* Value
LTS, deg									
Rupture	7.95 ± 0.40	7.1 to 8.8	8.40 ± 0.45	7.5 to 9.3	6.81 ± 0.84	5.0 to 8.5	1.60 ± 0.89	–0.7 to 3.9	.28
Intact	7.40 ± 0.61	6.1 to 8.6	9.36 ± 0.64	8.0 to 10.7	6.02 ± 0.84	4.3 to 7.7	3.34 ± 1.14	0.4 to 6.3	**.02**
Difference[b]	0.54 ± 0.73	–2.0 to 0.9	0.95 ± 0.99	–1.6 to 3.5	0.79 ± 1.05	–1.9 to 3.5			
P value[b]	.46		.77		.87				
MTS, deg									
Rupture	8.77 ± 0.38	8.0 to 9.5	9.34 ± 0.42	8.5 to 10.2	7.33 ± 0.71	5.9 to 8.8	2.00 ± 0.78	–0.0 to 4.0	.05
Intact	7.80 ± 0.51	6.8 to 8.8	9.55 ± 0.60	8.3 to 10.8	6.60 ± 0.67	5.1 to 8.0	3.00 ± 1.00	0.4 to 5.6	**.02**
Difference[b]	0.96 ± 0.64	–2.2 to 0.3	0.21 ± 0.87	–2.1 to 2.5	0.76 ± 0.92	–1.6 to 3.1			
P value[b]	.14		.99		.83				
CTS, deg									
Rupture	3.82 ± 0.23	3.3 to 4.2	3.75 ± 0.26	3.2 to 4.3	3.96 ± 0.46	3.0 to 4.9	0.21 ± 0.51	–1.1 to 1.5	.97
Intact	3.99 ± 0.31	3.3 to 4.6	4.04 ± 0.45	3.1 to 4.9	3.95 ± 0.45	3.0 to 4.9	0.09 ± 0.66	–1.1 to 1.8	.99
Difference[b]	0.18 ± 0.39		0.29 ± 0.57	–1.2 to 1.8	0.02 ± 0.60				
P value[b]	.65		.95		>.99				
MTD, mm									
Rupture	3.03 ± 0.09	2.8 to 3.2	3.00 ± 0.10	2.8 to 3.2	3.13 ± 0.19	2.7 to 3.5	0.13 ± 0.19	–0.4 to 0.6	.90
Intact	3.25 ± 0.12	2.9 to 3.5	2.81 ± 0.19	2.4 to 4.2	3.56 ± 0.19	3.3 to 3.8	0.74 ± 0.24	0.1 to 1.4	**.02**
Difference[b]	0.22 ± 0.15	–0.1 to 0.5	0.18 ± 0.21	–0.4 to 0.7	0.43 ± 0.23	–0.2 to 1.0			
P value[b]	.16		.84		.23				

[a] Boldface indicates statistically significant difference. CTS, coronal tibial slope; LTS, lateral tibial slope; MTD, medial tibial depth; MTS, medial tibial slope; SE, standard error.

[b] Difference between rupture and intact groups.

7.8; $P < .001$). Likewise, older patients were more likely to tear their ACL, with the risk increasing by 6% (odds ratio [OR], 1.06; 95% CI, 1.02-1.10) for every year of age ($P < .001$).

Female patients had a significantly greater (steeper) LTS (by 2.2° ± 0.7°; $P = .02$) and MTS (2.4° ± 0.6°; $P = .02$) than male patients. Conversely, female patients had a smaller MTD than male patients by 0.4 ± 0.15 mm ($P = .02$). Male and female patients did not differ in the CTS ($P = .97$). In the intact group alone, similar differences were observed between male and female patients (Table 1). However, we did not observe sex differences in any of the quantified indices in the rupture group ($P \geq .05$) (Table 1). Subgroup analysis also showed no significant differences (intact vs rupture) in any of the quantified indices within each sex ($P > .20$) (Table 1).

There were no differences between the intact and rupture groups in any of the quantified anatomic indices ($P > .10$) (Table 1). After adjusting for patient age, logistic regression did not associate the anatomic indices with the risk of an ACL tear in a noncontact injury among recreational alpine skiers ($P > .10$) (Table 2). Likewise, independent logistic regression on each sex showed no associations between anatomy and the risk of a noncontact ACL injury in either male or female patients ($P > .05$) (Table 2).

DISCUSSION

The objective of this study was to determine associations between morphological features of the tibial plateau and the risk of tearing the ACL as a result of a noncontact injury during recreational alpine skiing. The tibial plateau slopes (LTS, MTS, and CTS), concavity (MTD), and the risk of a noncontact ACL injury were not associated among

TABLE 2
Associations Between Quantified Anatomic Indices of the Tibial Plateau and the Risk of Sustaining an ACL Tear During a Noncontact Injury[a]

Anatomic Index	Odds Ratio	95% CI	Coefficient	SE	*P* Value
All patients					
LTS	1.04	0.9-1.2	0.05	0.05	.44
MTS	1.09	1.0-1.2	0.09	0.06	.13
CTS	0.95	0.8-1.2	–0.04	0.09	.65
MTD	0.71	0.4-1.1	–0.35	0.24	.16
Female patients					
LTS	0.91	0.8-1.1	–0.10	0.09	.28
MTS	0.97	0.8-1.2	–0.02	0.09	.80
CTS	0.92	0.7-1.2	–0.08	0.14	.59
MTD	1.40	0.7-3.1	0.34	0.38	.38
Male patients					
LTS	1.05	0.9-1.2	0.05	0.07	.49
MTS	1.07	0.9-1.3	0.07	0.09	.42
CTS	1.03	0.1-10.2	0.01	0.13	.98
MTD	0.51	0.2-1.1	–0.67	0.38	.08

[a] All analyses have been adjusted for patient age. There were no significant associations between the indices and the risk of an anterior cruciate ligament (ACL) tear. CTS, coronal tibial slope; LTS, lateral tibial slope; MTD, medial tibial depth; MTS, medial tibial slope; SE, standard error.

recreational alpine skiers. Furthermore, the risk of an ACL injury in both older and female skiers was increased. Women demonstrated steeper posterior-inferior directed slopes across both the medial and lateral compartments and a shallower (less concave) medial tibial plateau than men. While sex affected both the injury risk and anatomy, independent analyses of each sex did not associate the injury risk and anatomy. Also, no notable differences were observed in any of the quantified anatomic indices between the rupture and intact groups.

Alpine skiing is a popular sport worldwide, with an estimated 200 million participants around the globe.[22] Knee sprains are the most common injury in skiers, with approximately 30% of all injuries in adults.[12,45] Among these, ACL injuries account for the majority of knee sprains with 16%.[45] Similar to other high-risk sports, a great deal of research has been devoted to identifying ACL injury mechanisms and potential risk factors among skiers.[23,27,36] Despite efforts to characterize these factors for ACL injuries sustained during various sports (ie, basketball, volleyball, soccer, football), it is not clearly understood whether those findings translate into noncontact ACL tears observed in recreational alpine skiers. The current study is one of the first attempts to test this matter with regards to tibial plateau slopes and concavity. The mentioned anatomic features have been strongly related to the ACL injury risk in sports involving considerable jump landing.[6,7,30,34] However, our findings disagree, in part, with previous reports and do not associate these features of the tibial plateau and the risk of an ACL tear during a noncontact injury among recreational skiers.

The unique morphological characteristics of the tibiofemoral joint guide the motion of the tibia relative to the femur as the ACL is loaded to failure under high loading conditions.[15,17,24,34,38] ACL strain increases with impulsive compression loading with the knee near extension and a greater posterior-inferior directed slope of the tibial plateau. This combination induces anterior displacement, internal rotation of the tibia relative to the femur, and knee valgus.[34] Similarly, a greater LTS and MTS and a lower MTD (flatter medial tibial plateau) are associated with a higher risk of a noncontact ACL injury if patients are involved in sudden transitions from nonweightbearing to weightbearing conditions due to landing from a jump or a plant-and-pivot maneuver.[6,7,30,34]

In real cases of ACL injuries during basketball, volleyball, soccer, or football, numerous studies support the presence of a jump landing and a plant-pivot-cut maneuver with knees near extension.[9,28,29,35,44] In contrast, the common mechanism for noncontact ACL injuries during recreational alpine skiing induces excessive valgus–external rotation and extreme internal rotation of a hyperflexed knee, also called a "phantom foot."[13,23,27,36] Our missing association between the LTS, MTS, and MTD and ACL injury risk is consistent considering the lack of impulsive compression forces and the increased knee flexion associated with noncontact ACL injuries among recreational alpine skiers.[15,38] The current findings also did not relate the CTS and the risk of noncontact ACL injuries in recreational alpine skiers. These data agree with previous studies of athletic tasks involving jump landing and plant-pivot-cut maneuvers.[6,18] However, consistent with other studies, the tibial plateau anatomy differed significantly between sexes.[6,18] Female compared with male patients showed steeper posterior slopes of the tibial plateau (LTS and MTS) and a less concave medial tibial plateau (smaller MTD). These similarities are reassuring in a sense that our studied population was not anatomically different from those used in previous investigations in which significant associations between anatomy and the injury risk were reported.[6-8,11,18,20,40-43] Therefore, we assert that the risk of ACL injuries is more dependent on the type of sports rather than anatomic features alone. In this context, the injury mechanism is possibly more important.

As with any studies, there are several associated limitations. First, technical challenges exist when measuring with a 2-dimensional approach, that is, identifying the proper image slice to analyze, which can result in inconsistencies.[6] However, we used well-established, validated MRI measurement techniques to systematically and more consistently quantify the anatomy. These techniques helped us to address some errors associated with quantifying the anatomy from radiographs, in particular for measuring the sagittal tibial slope. We also measured each anatomic index in each knee twice independently to reduce errors and personal bias. The excellent ICC adds confidence in accuracy. Second, because female patients are at a greater risk of rupturing their ACL during recreational alpine skiing, there were a disproportionate number of female versus male patients in each group. This incongruence may have affected the results. We have tried to minimize the effect of this population heterogeneity by taking into account the effect of sex on all associations using subgroup analysis. Similarly, there were a substantially greater number of patients with a ruptured ACL compared with those with no ACL injury, which may have skewed the findings. This is consistent with the trend in our practice as the majority of patients admitted after a noncontact incident show a torn ACL revealed by MRI. This factor was taken into account when performing a priori power analysis by assuming a ratio of 1:2 for the desired sample size. Regarding the male and female subgroups, power was reduced in case of a nonsignificant result. Therefore, these results should be reviewed with caution. Further information on the exact injury mechanism could not be verified in the present study and stays subjective. However, in all patients, a noncontact injury was reported as plausible. Finally, the study was conducted retrospectively with no matching between injured patients and controls, which may have confounded some of the findings. Despite these limitations, there were notable strengths associated with this study. The large sample size of 121 patients with a realistic sex distribution between groups as seen in our clinic enabled us to assess potential differences between injured and noninjured groups with an acceptable statistical power.

CONCLUSION

The sagittal and coronal slopes (LTS, MTS, CTS), as well as the concavity of the medial tibial plateau (MTD), were not associated with the risk of sustaining an ACL tear during a noncontact injury among recreational alpine skiers. Our data revealed significant sex differences in the ACL injury risk and all quantified anatomic indices except the CTS. Overall, these findings emphasize how important it is to include the sports type as a confounding factor when assessing associations between anatomy and the ACL injury risk. Such findings may in turn help to better characterize the "at-risk" population for specific sports and athletic activity.

REFERENCES

1. Agel J, Arendt EA, Bershadsky B. Anterior cruciate ligament injury in National Collegiate Athletic Association basketball and soccer: a 13-year review. *Am J Sports Med*. 2005;33(4):524-530.
2. Alentorn-Geli E, Myer GD, Silvers HJ, et al. Prevention of non-contact anterior cruciate ligament injuries in soccer players, part 1: mechanisms of injury and underlying risk factors. *Knee Surg Sports Traumatol Arthrosc*. 2009;17(7):705-729.
3. Anderson AF, Dome DC, Gautam S, Awh MH, Rennirt GW. Correlation of anthropometric measurements, strength, anterior cruciate ligament size, and intercondylar notch characteristics to sex differences in anterior cruciate ligament tear rates. *Am J Sports Med*. 2001;29(1):58-66.
4. Arendt EA, Agel J, Dick R. Anterior cruciate ligament injury patterns among collegiate men and women. *J Athl Train*. 1999;34(2):86-92.
5. Bates NA, McPherson AL, Rao MB, Myer GD, Hewett TE. Characteristics of inpatient anterior cruciate ligament reconstructions and concomitant injuries [published online December 16, 2014]. *Knee Surg Sports Traumatol Arthrosc*. doi:10.1007/s00167-014-3478-3.
6. Beynnon BD, Hall JS, Sturnick DR, et al. Increased slope of the lateral tibial plateau subchondral bone is associated with greater risk of noncontact ACL injury in females but not in males: a prospective cohort study with a nested, matched case-control analysis. *Am J Sports Med*. 2014;42(5):1039-1048.
7. Beynnon BD, Vacek PM, Sturnick DR, et al. Geometric profile of the tibial plateau cartilage surface is associated with the risk of non-contact anterior cruciate ligament injury. *J Orthop Res*. 2014;32(1):61-68.
8. Bisson LJ, Gurske-DePerio J. Axial and sagittal knee geometry as a risk factor for noncontact anterior cruciate ligament tear: a case-control study. *Arthroscopy*. 2010;26(7):901-906.
9. Boden BP, Dean GS, Feagin JA Jr, Garrett WE Jr. Mechanisms of anterior cruciate ligament injury. *Orthopedics*. 2000;23(6):573-578.
10. 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.
11. 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.
12. Deibert MC, Aronsson DD, Johnson RJ, Ettlinger CF, Shealy JE. Skiing injuries in children, adolescents, and adults. *J Bone Joint Surg Am*. 1998;80(1):25-32.
13. Ettlinger CF, Johnson RJ, Shealy JE. A method to help reduce the risk of serious knee sprains incurred in alpine skiing. *Am J Sports Med*. 1995;23(5):531-537.
14. Fowler JR, Ilyas AM. The accuracy of digital radiography in orthopaedic applications. *Clin Orthop Relat Res*. 2011;469(6):1781-1784.
15. 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.
16. Griffin LY, Agel J, Albohm MJ, et al. Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. *J Am Acad Orthop Surg*. 2000;8(3):141-150.
17. 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.
18. 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.
19. Hewett TE, Di Stasi SL, Myer GD. Current concepts for injury prevention in athletes after anterior cruciate ligament reconstruction. *Am J Sports Med*. 2013;41(1):216-224.
20. 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:S109-S114.
21. Hudek R, Schmutz S, Regenfelder F, Fuchs B, Koch PP. Novel measurement technique of the tibial slope on conventional MRI. *Clin Orthop Relat Res*. 2009;467(8):2066-2072.
22. Hunter RE. Skiing injuries. *Am J Sports Med*. 1999;27(3):381-389.
23. Jarvinen M, Natri A, Laurila S, Kannus P. Mechanisms of anterior cruciate ligament ruptures in skiing. *Knee Surg Sports Traumatol Arthrosc*. 1994;2(4):224-228.
24. Kiapour AM, Kiapour A, Goel VK, et al. Uni-directional coupling between tibiofemoral frontal and axial plane rotation supports valgus collapse mechanism of ACL injury. *J Biomech*. 2015;48(10):1745-1751.
25. Kiapour AM, Murray MM. Basic science of anterior cruciate ligament injury and repair. *Bone Joint Res*. 2014;3(2):20-31.
26. Kiapour AM, Quatman CE, Goel VK, Wordeman SC, Hewett TE, Demetropoulos CK. Timing sequence of multi-planar knee kinematics revealed by physiologic cadaveric simulation of landing: implications for ACL injury mechanism. *Clin Biomech (Bristol, Avon)*. 2014;29(1):75-82.
27. Koehle MS, Lloyd-Smith R, Taunton JE. Alpine ski injuries and their prevention. *Sports Med*. 2002;32(12):785-793.
28. Koga H, Nakamae A, Shima Y, et al. Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball. *Am J Sports Med*. 2010;38(11):2218-2225.
29. Krosshaug T, Nakamae A, Boden BP, et al. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. *Am J Sports Med*. 2007;35(3):359-367.
30. Lipps DB, Oh YK, Ashton-Miller JA, Wojtys EM. Morphologic characteristics help explain the gender difference in peak anterior cruciate ligament strain during a simulated pivot landing. *Am J Sports Med*. 2012;40(1):32-40.
31. Lohmander LS, Englund PM, Dahl LL, Roos EM. The long-term consequence of anterior cruciate ligament and meniscus injuries: osteoarthritis. *Am J Sports Med*. 2007;35(10):1756-1769.
32. Lohmander LS, Ostenberg A, Englund M, Roos H. High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. *Arthritis Rheum*. 2004;50(10):3145-3152.
33. Mather RC 3rd, Koenig L, Kocher MS, et al. Societal and economic impact of anterior cruciate ligament tears. *J Bone Joint Surg Am*. 2013;95(19):1751-1759.
34. McLean SG, Lucey SM, Rohrer S, Brandon C. Knee joint anatomy predicts high-risk in vivo dynamic landing knee biomechanics. *Clin Biomech (Bristol, Avon)*. 2010;25(8):781-788.
35. Olsen OE, Myklebust G, Engebretsen L, Bahr R. Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. *Am J Sports Med*. 2004;32(4):1002-1012.
36. Pressman A, Johnson DH. A review of ski injuries resulting in combined injury to the anterior cruciate ligament and medial collateral ligaments. *Arthroscopy*. 2003;19(2):194-202.
37. Shelbourne KD, Davis TJ, Klootwyk TE. The relationship between intercondylar notch width of the femur and the incidence of anterior cruciate ligament tears: a prospective study. *Am J Sports Med*. 1998;26(3):402-408.

38. 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.
39. 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.
40. 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.
41. 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.
42. Sturnick DR, Vacek PM, DeSarno MJ, et al. Combined anatomic factors predicting risk of anterior cruciate ligament injury for males and females. *Am J Sports Med*. 2015;43(4):839-847.
43. Todd MS, Lalliss S, Garcia E, DeBerardino TM, Cameron KL. The relationship between posterior tibial slope and anterior cruciate ligament injuries. *Am J Sports Med*. 2010;38(1):63-67.
44. Walden M, Krosshaug T, Bjorneboe J, Andersen TE, Faul O, Hagglund M. Three distinct mechanisms predominate in non-contact anterior cruciate ligament injuries in male professional football players: a systematic video analysis of 39 cases. *Br J Sports Med*. 2015;49(22):1452-1460.
45. Warme WJ, Feagin JA Jr, King P, Lambert KL, Cunningham RR. Ski injury statistics, 1982 to 1993, Jackson Hole Ski Resort. *Am J Sports Med*. 1995;23(5):597-600.