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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

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Abstract

Background: There is an emerging consensus that increased posterior-inferior directed slope of the subchondral bone portion of the tibial plateau is associated with increased risk of suffering an anterior cruciate ligament (ACL) injury; however, most of what is known about this relationship has come from unmatched case-control studies. These observations need to be confirmed in more rigorously designed investigations.

Hypothesis: Increased posterior-inferior directed slope of the medial and lateral tibial plateaus are associated with increased risk of suffering a noncontact ACL injury.

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

Methods: In sum, 176 athletes competing in organized sports at the college and high school levels participated in the study: 88 suffering their first noncontact ACL injury and 88 matched controls. Magnetic resonance images were acquired, and geometry of the subchondral bone portion of the tibial plateau was characterized on each athlete bilaterally by measuring the medial and lateral tibial plateau slopes, coronal tibial slope, and the depth of the medial tibial plateau. Comparisons between knees of the same person were made with paired *t* tests, and associations with injury risk were assessed by conditional logistic regression analysis of ACL-injured and control participants.

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[||]References 3, 7–10, 16, 19, 23–25, 28–30.

Results: Controls exhibited side-to-side symmetry of subchondral bone geometry, while the ACL-injured athletes did not, suggesting that the ACL injury may have changed the subchondral bone geometry. Therefore, the uninjured knees of the ACL-injured athletes and the corresponding limbs of their matched controls were used to assess associations with injury risk. Analyses of males and females as a combined group and females as a separate group showed a significant association between ACL injury risk and increased posterior-inferior directed slope of the lateral tibial plateau slope. This relationship was not apparent when males were analyzed as a group. Multivariate analyses indicated that these results were independent of the medial tibial plateau slope, coronal tibial slope, and depth of the medial tibial plateau, which were not associated with ACL injury.

Conclusion: There is a 21.7% increased risk of noncontact ACL injury with each degree increase of the lateral tibial plateau slope among females but not among males. The medial tibial plateau slope, coronal tibial slope, and depth of the medial tibial plateau were not associated with risk of injury for females or males.

Keywords

anterior cruciate ligament; biomechanics of ligament; injury prevention; knee; ligaments

Anterior cruciate ligament (ACL) disruption and concomitant injury to the menisci and articular cartilage are associated with increased risk of the early onset of posttraumatic osteoarthritis, regardless of whether non-surgical or surgical treatment is chosen.[13,14] This has focused research on determining the intrinsic and extrinsic factors associated with risk of ACL injury so that prevention strategies can be developed and those at increased risk of this devastating injury and sequela can be identified and targeted for an intervention.[21]

The geometry of the articular and underlying subchondral bone surfaces of the knee is important for transmitting loads across the joint, and it has an important effect on the knee's biomechanical response and associated risk of suffering ACL trauma. For example, the magnitude of ACL strain values produced by impulsive compressive loading of the tibiofemoral joint (eg, that produced when landing from a jump[11,15]) and the anterior directed translation of the tibia relative to the femur during common weightbearing activities[1] are directly related to the posterior-inferior directed slopes of the subchondral bone portion of the tibial plateau. When these observations are considered in combination with studies that have shown an increase in the posterior-inferior directed slope of the subchondral bone of the tibial plateau in individuals suffering ACL injury,[‖] insight is provided concerning one of the underlying mechanisms that may be responsible for an increased risk of suffering noncontact ACL injury.[7,8,19] However, the results from these studies have been mixed.[29,30] Most studies have revealed that an increased slope of the tibia within the lateral compartment is associated with an increased risk of suffering ACL injuries.[3,8,10,19,22,23,25] Others have reported that the slope of the medial compartment of the tibia[8,24,28] and the medial tibial plateau depth of concavity[8,10] are also associated with risk of suffering ACL injury. A recent study has reported no relationship between tibial plateau

One or more of the authors has declared the following potential conflict of interest slope and risk of ACL injury.[27] Additionally, there exist discrepancies with regard to whether these geometric measures are associated with ACL injury risk in males and females. In part, this can be attributed to the study designs that have unmatched or inadequately matched controls and have suffered from confounding factors, possibly introduced by comparing injured and uninjured participants who differed in age and exposure to at-risk activities, who participated in different activities, and who had different levels of play and different playing conditions—all of which could have introduced differing opportunities to suffer ACL injury. In addition, different measurement approaches (eg, imaging techniques: magnetic resonance imaging [MRI], computed tomography, or radiographs), definition of the coordinate system located in the tibia used to measure plateau geometry, and limb orientation may also have contributed to contrasting results.[29,30]

The objective of this investigation was to build on prior retrospective unmatched case-control studies by conducting a prospective cohort study with a nested, matched case-control analysis that examined the relationship between geometry of the subchondral bone portion of the tibial plateau and the risk of suffering a noncontact ACL injury. A key feature of this study design is that controls are randomly selected from comparably exposed cohort members with no ACL injury before or at the time that the case was injured. With this sampling scheme, the odds ratios obtained from nested case-control analysis are comparable with the relative risk estimates from a full analysis of all cohort members, with only a modest reduction in statistical power. We hypothesized that individuals who are at increased risk of suffering noncontact ACL injury would demonstrate increased posterior-inferior directed slope of their tibial plateau subchondral bone in comparison to those at lower risk.

MATERIALS AND METHODS

Before data collection, this investigation was approved by our institutional review board, and all participants provided written informed consent. This report is based on analysis of MRI data obtained as part of a larger prospective cohort study with a nested case-control analysis that was designed to develop a comprehensive multivariate model characterizing the combination of risk factors associated with noncontact ACL injury[20] (Beynnon BD, Vacek PM, Tourville TW, et al. "Univariate Analysis of Risk Factors for Noncontact Anterior Cruciate Ligament Injury." Unpublished data) and expanding on the recent study that focused on geometry of the surface of the tibial articular cartilage.[2] The larger study[20] was designed to select 3 matched controls for each ACL-injured participant, but because of the costs associated with MRI acquisition, only 1 control per ACL-injured participant was selected to undergo MRI; consequently, the analysis in the current report is based on one-to-one matching. Over a 4-year time interval that commenced in the fall of 2008, individuals providing medical care to sports teams from 36 institutions (28 high schools and 8 colleges) identified and approached participants about participation in the study when a noncontact ACL injury was suspected. The high school-level sports that were studied included soccer, basketball, and lacrosse for girls and boys; field hockey for girls; and football for boys. The same sports were studied at the college level for men and women, with the addition of rugby for men and women and volleyball for women. Noncontact ACL injury was defined as an injury that did not involve direct impact to the knee. The diagnosis was made by an orthopaedic surgeon and then confirmed by MRI and arthroscopic visualization at the time of surgery. ACL-injured athletes were included if they suffered their first ACL injury during participation in organized sport and had no history of an ACL injury to either limb. At the same time that the injury was suffered, 3 matched controls were randomly selected from the injured participant's sports team and, if they had not suffered a prior ACL injury, were invited to participate. This approach was used to achieve matching by sex, sport, and activity level and to ensure a similar age and exposure to the activities and conditions that were associated with the ACL injury. One control per case was then randomly selected for the current MRI-based study.

After enrollment, ACL-injured participants and controls underwent bilateral MRI with a Philips Achieva 3.0T TX scanner system (Philips Medical Systems, Best, Netherlands). Participants had both knees scanned with the joint placed in an extended position inside an 8-channnel SENSE knee coil. Sagittal-plane MRI data were acquired 3-dimensionally with Tl-weighted fast-field echo scans with a slice thickness of 1.2 mm and a pixel size of 0.3 × 0.3 mm.

After MRI acquisition, DICOM images were postprocessed by manually segmenting the sagittal-plane MRI images of the medial and lateral compartments of the tibial plateau with a Cintiq 21UX digitizing tablet (Wacom Technology Corporation, Vancouver, Washington, USA) with OsiriX software v. 3.6.1 (Pixmeo, Bernex, Switzerland). Segmentation of the sagittal-plane cuts was started at the surface of the first distinguishable subchondral bone slice from the periphery of each compartment, was bounded by the most anterior and posterior regions of subchondral bone on each slice, and was completed when the tibial spine reached its maximum height (Figure Al, available online at http://ajsm.sagepub.com/supplemental). Custom MATLAB code was developed to postprocess the subchondral bone surface data that were acquired in the coordinate system of the MRI scanner and transform them to a coordinate system located in the tibia[2] (Figure 1). This approach allowed us to characterize the geometry of the subchondral bone portion of the plateau in a reproducible and reliable manner within and between participants. Linear interpolation of the subchondral bone surface data was performed to generate data in a parasagittal (x-z) plane at 1.0-mm increments along the x-axis (anterior-posterior) direction with planes located 1.0 mm apart in the y-axis (medial-lateral) direction. The approach described by Hashemi et al[7] was used to determine the location where the lateral, medial, and coronal slopes of the tibial plateau (LTS, MTS, and CTS, respectively) and the depth of the medial tibia plateau (MTD) were measured. To accomplish this, the centers of the most distal aspects of the medial and lateral femoral condyles were identified in a transverse plane. On the corresponding sagittal slice, the MTS and LTS were measured as the angle between a line that joined the peak points on the anterior and posterior rims of the plateau and a line constructed perpendicular to the z-axis (inferior-superior directed axis) of the tibia (Figure 2, A and B).[8] The depth of concavity of the medial tibial plateau was measured by constructing a line between the crests of the anterior and posterior rims of the tibial plateau in the same plane that the MTS was measured; the greatest depth of concavity as measured perpendicularly from this line was the MTD (Figure 2C). We then moved to the frontal plane and located the magnetic resonance image where both medial and lateral tibiofemoral articulation occurred, and we characterized the CTS by constructing a line tangent to the medial-and lateral-most rims of the tibial plateau and by measuring the angle of this line relative to the *y*-axis (medial-lateral) of the tibia (Figure 2D).

STATISTICAL ANALYSIS

Reliability of subchondral bone geometry measurements were assessed with variance component analysis to obtain estimates of the variability between participants, between examiners, and within examiners. Intraclass correlation coefficients (ICCs) were then computed with the methodology described by Eliasziw et al[5] for concurrently assessing inter-and intrarater reliability.

Prior work has demonstrated that the geometry of tibiofemoral articular cartilage and underlying subchondral bone undergoes substantial changes after ACL injury.[26] Consequently, our initial step was to determine if ACL trauma modified the measurements of subchondral bone geometry (LTS, MTS, CTS, and MTD). This was evaluated with paired *t* tests to compare the subchondral bone geometry measurements of the participants' injured and uninjured legs. Comparable tests were performed in control participants to confirm that such differences were absent in individuals who had not suffered prior joint trauma. Based on the results of these analyses, the subchondral geometry measurements (LTS, MTS, CTS, and MTD) of the uninjured knees of the injured participants and the corresponding knees of the matched controls were used in univariate conditional logistic regression analyses to assess their associations with the risk of noncontact ACL injury (the primary study hypothesis). Multivariate conditional logistic regression analysis assessed the independent effects of these measurements. All analyses were performed with combined data from males and females, as well as separately for males and females, and P values of .05 or less were considered statistically significant.

RESULTS

The overall study enrolled 109 participants who suffered their first noncontact ACL injury[20]; 21 of these individuals did not have adequate MRI data (owing to the presence of hardware, incomplete data acquisition, or an insufficient length of the tibia on the images to establish a bony referenced coordinate system). This produced a sample size of 88 case-control pairs (176 participants) for this study. Sixty-one of these case-control pairs were female (122 participants) and 27 were male (54 participants). Seventy-eight of the matched case-control pairs (156 individuals) participated in an earlier investigation that studied the relationship between tibial plateau articular cartilage surface geometry and risk of noncontact ACL injury.[1] Data on participant age, height, and weight are presented in Table 1. Based on all study participants, the time interval between the noncontact ACL injury and MRI ranged between 1 and 110 days (mean, 23.9 days). There was no significant difference between the means of males (22.3 days; range, 1–103 days) and females (24.6 days; range, 1–110) (P = .71).

A random sample of 26 knees (1 knee per participant) was read at 2 time points by 2 blinded investigators to assess the reproducibility of LTS, MTS, CTS, and MTD measurements. The ICCs for intrarater reliability ranged from 0.89 for LTS to 0.96 for MTS. Interrater ICCs were slightly lower (ranging from 0.82 to 0.88), but all measurements reported here were made by the same investigator.

Univariate Analysis

Comparison of Side-to-Side Differences in Tibial Plateau Subchondral Bone Geometry of ACL-Injured and Control Participants.—For the ACL-injured participants, comparison of the tibial plateau subchondral bone variables between the injured and contralateral normal knees revealed significant differences (Table 2). When data from both females and males were analyzed together, the mean CTS for the injured knees was significantly larger ($P = .009$) than the mean for the uninjured knees. When females were examined alone, the difference in CTS remained significant ($P = .036$). When males were examined alone, the CTS was not different, but the LTS was significantly different between the injured and uninjured knees ($P = .006$).

The same comparisons in the control participants (injured vs uninjured knee as defined by the injury to the matched injured participant) showed no significant differences in any of the tibial plateau subchondral bone variables when females and males were analyzed together and as separate groups (Table A1, available online).

Comparison of Subchondral Bone Geometry Between ACL-Injured and Control Participants.—The above finding of differences in tibial plateau subchondral bone geometry between the injured and contralateral limbs of the ACL-injured participants but no differences between the corresponding knees of the control participants indicates that the ACL injury and early healing response may have changed the subchondral bone geometry. As a result, we tested our primary study hypothesis by comparing the uninjured sides of the ACL-injured participants with the corresponding knees of the controls (Table 3).

Univariate analysis of data from the males and females as a combined group demonstrated that an increase in LTS was significantly associated with an increased risk of suffering noncontact ACL injury ($P = .008$). The ACL-injured participants had greater (less negative or more positive) LTS values than did uninjured controls, describing a greater posterior-inferior directed plateau, or conversely a decreased posterior-superior directed slope. For each 1-degree increase in LTS (an increase in the posteriorinferior directed slope of the plateau), there was a 14.6% increase in the risk of suffering a noncontact ACL injury (Table 4). There were no significant associations with risk for MTS, CTS, or MTD (Table 4). Similarly, analysis of data from the females revealed that an increase in LTS was significantly associated with an increased risk of suffering noncontact ACL injury (each 1-degree increase in LTS was associated with a 21.7% increase in risk; $P = .003$); there were no significant associations for the remaining variables (Table 4). When males were analyzed as a group, there was no evidence for associations between risk of noncontact ACL injury and any of the tibial plateau subchondral bone variables studied (Table 4).

Multivariate Analysis

Comparison of Subchondral Bone Geometry Between ACL-Injured and Control Participants.—Multivariate analysis of the male and female data as a combined group demonstrated that the increase in risk of suffering a noncontact ACL injury associated with increases in LTS remained significant (*P* = .007) after adjustment for MTS, CTS, and MTD and that these other subchondral bone geometry measures were not associated with risk of injury (Table 5). Each 1-degree increase of LTS was associated with an 18.4% increase in risk of suffering a noncontact ACL injury. Regarding females as a group, each 1-degree increase in LTS was associated with a 31.9% increase in risk of suffering noncontact ACL injury (*P* = .002) after adjustment for MTS, CTS, and MTD, none of which contributed significantly to injury risk (Table 5). Among males, there were no significant associations with risk of noncontact ACL injury when all the tibial plateau variables were considered in combination (Table 5).

DISCUSSION

The objective of this study was to measure the geometry of the tibial plateau subchondral bone and determine if increased posterior-inferior directed slopes of the medial and lateral compartments are associated with increased risk of suffering noncontact ACL injury. Both univariate and multivariate analyses produced similar findings: an increase in LTS (increased posterior-inferior directed slope of the lateral tibial plateau) was significantly associated with an increase in risk of suffering noncontact ACL injury when males and females were considered as a combined group. However, separate analysis of males and females revealed that this result was attributable only to females. Among males, there was no evidence of a relationship between the subchondral bone measurements and risk of ACL injury. Analysis was also performed considering the difference in slopes between the lateral and medial compartments of the tibia (LTS-MTS), and this was found to be associated with increased risk of suffering noncontact ACL injury. However, very little was added in terms of increased risk in comparison with the analysis of LTS alone; consequently, the difference in slope was not considered to be more important than just the slope of the lateral compartment in isolation. Increased body weight and body mass index were found to be associated with increased risk of suffering noncontact ACL injury in the larger cohort, and we subsequently performed additional analyses to adjust for each of these variables (Beynnon BD, Vacek PM, Tourville TW, et al; unpublished data). This did not change the findings of either the univariate or multivariate analysis regarding the associations between subchondral bone geometry and ACL injury risk. Although height was not associated with risk of suffering noncontact injury, we included it in the statistical analyses and obtained similar results.

These findings are consistent with and build on earlier analysis of the geometry of the overlying articular cartilage surface in a subset of the participants in the current study.[2] That work revealed significant differences in the polynomial expressions used to characterize the articular surface geometry of the ACL-injured athletes compared with controls. When males and females were analyzed together, injured participants demonstrated a posteriorinferior directed orientation of the articular surface of the tibia relative to the superior-inferior axis of the tibia in both medial and lateral compartments of the tibia, while the controls were more likely to show a posterior-superior directed orientation in both compartments. The same relationship was found when females were analyzed as a group; however, there were no significant differences between male cases and controls.[2]

Our prior and current results indicate that the geometry of the midportion of the lateral tibial plateau has a strong influence on the risk of suffering ACL injury in females but not males and that the geometry of the medial compartment may have less of an influence on injury risk. These findings are important because during the process of suffering an ACL injury, the geometric profile of the tibiofemoral joint guides displacement of the tibia relative to the femur as the ligament is loaded to failure; furthermore, an increased posterior-inferior orientation of the lateral plateau (increased LTS) would act to produce a combination of anterior displacement and internal rotation of the tibia relative to the femur, which would increase ACL strain values. This mechanism was introduced by Simon et al,[19] and the findings from the current study support this earlier work. This is a concern when the injury occurs during activities that involve impulsive loading with the knee near extension—for example, when the joint transitions from nonweightbearing to weightbearing conditions during landing from a jump or a plant and pivot maneuver—because the posterior-inferior directed slope of the subchondral bone portion of the tibial plateau is directly related to the landing impact-induced ACL strain values.[15] In addition, when the knee is near extension, the orientation of the muscles that span the knee does not allow for effective control of anterior translation and internal rotation of the tibia produced by the impulsive loads that are associated with most noncontact ACL tears.

The finding that increased LTS is the primary characteristic of the tibial plateau subchondral bone geometry that is associated with increased risk of noncontact ACL injury confirmed a prior report by Simon et al.[19] However, it supports only a portion of the earlier work by Hashemi et al[8] that reported males with increased LTS and MTS combined with decreased MTD were at increased risk of suffering ACL trauma, as were females with increased LTS combined with decreased MTD. The contrasting findings between our current study and the earlier one may be explained by differences in study design, entry criteria, and the approaches used to measure geometry of the tibial plateau subchondral bone.

The current report used a prospective design to identify, recruit, and enroll participants immediately after they suffered their first noncontact ACL trauma, and it included a nested case-control component in which controls were randomly selected from among injured participants' teammates. This approach ensured that injured participants and controls were matched by sex, age, type of sport activity, level of play, and playing conditions and that ACL-injured athletes and controls had a similar opportunity to be injured. In contrast, earlier case-control studies did not use the same prospective approach to recruit and enroll study participants and did not include matching in either control selection or data analysis. These studies therefore did not control for potential confounding introduced by comparing injured and uninjured participants who were of different ages, participated in different sports, took part in different levels of play, participated with different playing conditions, had different knee injury/disease histories that may have affected the measures of tibial plateau geometry, and had different opportunities to suffer injury.

The approach used in the current study provided a controlled investigation of a population of young active individuals who are at the greatest risk of suffering their first noncontact ACL injury. The same definition of what constituted a noncontact ACL injury was applied to the entire cohort, and we thus knew where participants came from in terms of the type of injury suffered and their injury and health history. In addition, the current study was not confounded by other covariates, such as prior ACL injury or disease that may have had an effect on subchondral bone geometry.

Another important difference that may explain the divergent findings among studies is the approach that was used to measure subchondral bone geometry. The current study acquired MRI data in 3 dimensions via a standardized approach defined in a coordinate system located relative to the MRI scanner, and these data were then transformed to a coordinate system located in the tibia via a standardized approach. This allowed 3-dimensional measurements to be made in a reproducible and reliable manner both within and between participants. We evaluated the reliability associated with measuring geometry of the subchondral bone portion of the tibial plateau (inter-and intraexaminer reliability of LTS, MTS, CTS, and MTD) and found ICC values that demonstrated our capacity to make the measurements in a highly repeatable manner and were similar to those presented by Lipps et al.[12]

Earlier reports have not used the same approach, and this may have contributed to measurement error. For example, we made comparisons of the internal-external rotational orientation of the MRI sagittal plane (the original data that were acquired from the MRI scanner and the plane that a majority of prior reports have used to measure tibial plateau subchondral bone geometry) relative to the orientation measured in the tibial coordinate system that we established (the data in the *x-z* plane that was used to measure subchondral bone geometry). This revealed no side-to-side differences between knees for injured participants and controls; however, the tibia of both the injured and uninjured knees of the ACL-injured participants had significantly greater internal rotation orientation in comparison with the corresponding knees of the controls. This is a concern because we found that this increase was correlated with an increase in MTS and MTD values. This finding indicates that a bias may be introduced between measurements made in the ACL-injured participants and controls if they were referenced to a coordinate system located in the MRI scanner and not relative to a coordinate system located in the tibia.

Additionally, the current study established a reproducible and consistent approach to define the inferior-superior directed axis of the tibia, and this was important because it was used as the reference axis from which the subchondral bone slopes were measured. Tibias are not uniform in shape; consequently, the orientation of its long axis is dependent on the proportion of the tibia that is used to establish it. For example, if cases were consistently larger than controls, there would be a bias in the proportion of tibia present in the MRI field of view that could be scanned. Not controlling for the proportion of the tibia acquired and the landmarks used to define the long axis of the tibia could introduce a bias into the orientation of the tibial axis and subsequently introduce error into measurement of the tibial plateau slopes.[12] To address this concern, we defined the superior-inferior axis of the tibia using consistent locations on the tibia that were proportional to its size; furthermore, to ensure that all study participants were included, the portion of the tibia that was used to establish its superior-inferior axis had to be located proximally and did not include the entire length of the tibia. This approach created a superior-inferior axis of the tibia that was not aligned colinear with an axis located central to the entire length of the tibia, and it resulted in both posterior-inferior and posterior-superior directed slope values for MTS and LTS. It is important to highlight that this produced only a systematic, or fixed, offset in MTS and LTS relative to prior reports that used different approaches to establish the long axis of the tibia[6] and did not confound the statistical analysis, interpretation of the findings, and the conclusions that were made. This is evidenced by the fact that our tibial plateau slope values and statistical findings were very similar to those reported by Simon et al,[19] who used a similar approach to establish the superior-inferior axis of the tibia.

There were important strengths and weakness associated with this study. A major strength of the nested case-control design and statistical analysis is that it controls for exposure to at-risk activities. As a consequence, the resulting odds ratios are mathematically comparable with estimates of relative risk that would be obtained from a prospective approach, in which all individuals in a cohort are followed over time and the data are used in a Cox regression analysis to model time to injury.[4] However, our approach does carry with it the assumption that the ACL-injured knee was not altered by the index trauma that disrupted the ligament to the extent that the potential risk factors under consideration were modified and that measurements made on the uninjured knee are valid proxy measures for the injured knee before trauma. A fully prospective approach that would not require this assumption was not feasible, because it would have required preparticipation/ preinjury MRI on both knees for all athletes on all teams followed in this study, which, we estimate, would have been more than 8000 participants to generate the same number of injured participants.[20] Therefore, our first step was to test whether the injury and initial healing response modified subchondral bone geometry by making side-to-side comparisons within the ACL-injured participants and within controls. This revealed no side-to-side differences for the controls (Table A1, available online) but several differences for the ACL-injured athletes (Table 2). This finding suggests that the subchondral bone geometry of the ACL-injured knee may have been altered by the injury, and consequently, we used the uninjured knee of the ACL-injured athletes and the corresponding side of the controls to test the primary study hypothesis. However, in case the observed geometry was indeed the preinjury anatomy of the injury knees, we repeated the case-control analysis using the ACL-injured knee of the injured participants and the corresponding side of the controls, and the results for LTS were consistent with those obtained for the uninjured leg. Every effort was made to recruit an equal number of males and females; however, the sample size was approximately 2 times larger for the females (n = 61) in comparison with the males (n = 27). Thus, the separate analyses of females and males had different statistical power, and this may have contributed, at least in part, to the absence of statistically significant associations with ACL injury risk among the males. For example, we had 80% power to detect a relative risk (as estimated by the odds ratio) of 1.28-per-unit increase in LTS for males, compared with a relative risk of 1.13 for females. However, the odds ratio for LTS that was observed in males (0.985) was not similar to the highly significant odds ratio of 1.217 in females. This suggests that a larger sample of males may result in the same nonsignificant finding.

The geometry of the articular surfaces and underlying subchondral bone of the tibia may be affected by how loads are distributed across its medial and lateral compartments during growth and development. For example, during development, females demonstrate increased valgus about their knee in comparison to males during standing and landing from a jump; as a result, it may be that females transmit a larger proportion of their intersegmental compressive loads across the lateral compartment of their knee during activities of daily living and sport in comparison with males. This may have a pronounced effect on the geometry and orientation of the lateral aspect of the knee for certain females, a much smaller effect on males, and may explain why geometry of the lateral compartment was associated with increased risk of injury for females but not males.

In the at-risk age group that we studied, subchondral bone geometry is largely a nonmodifiable risk factor; therefore, ACL injury prevention research should continue to consider developing intervention programs that attenuate the impact loads transmitted across the knee. As suggested by Oh et al,[17,18] this could be accomplished through changes in landing biomechanics, footwear, or the playing surfaces, in an effort to decrease the impulsive joint forces that contribute to anterior translation and internal rotation of the tibia relative to the femur. This may reduce the magnitude of strain that the ACL must resist during impulsive loading of the knee and may thus reduce the risk of suffering an ACL injury. The focus of our current work, however, is to elucidate how the 3-dimensional geometry of the articular surface of the tibia is associated with risk of injury to the ACL and how it acts in combination with other characteristics of the knee, such as the extensor moment arm, and the geometry of the ACL, meniscus, articular surface, and femoral notch. This information is necessary to gain a complete understanding of the combination of risk factors (both modifiable and nonmodifiable) for ACL injury, upon which a comprehensive multivariate model of injury risk can be determined. With this multivariate model, it will be possible to develop intervention strategies to reduce the incidence of noncontact ACL injuries and target these programs at those who are at increased risk for suffering this debilitating injury.

In conclusion, we found that females are at increased risk of suffering a noncontact ACL injury with an increase in the posterior-inferior directed slope of the subchondral bone portion of the lateral tibial plateau and that this relationship did not exist for males. Multivariate analyses revealed that these findings were independent of MTS, CTS, and MTD, which were not associated with ACL injury. This information may be used to help identify females who are at increased risk for suffering ACL injury or repeated injury of this kind so that an intervention can be targeted at them.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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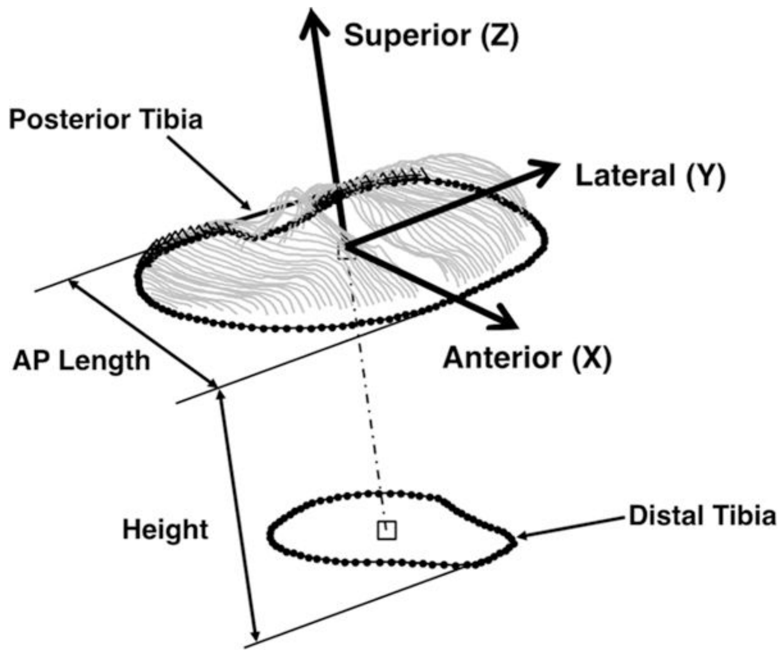

Figure 1.

Segmented data (gray lines) relocated to tibial coordinate system. The long axis of the tibial coordinate system is defined by the direction connecting the centroids (black open squares) of the proximal and distal transverse plane outlines of tibial cortical bone (black dotted lines). The proximal outline is made at the transverse level just below the tibial articular cartilage surface. The distal outline is made at an inferior height equal to the anterior-posterior length of the proximal tibia outline. Medial and lateral outlines of the posterior aspects of the tibial cortices are made at the proximal level of the posterior cruciate ligament insertion. The medial-lateral direction of the tibial coordinate system is defined by the direction that passed through the most posterior points of the medial and lateral tibial outlines (black open triangles) and perpendicular to the defined superior-inferior axis. The posterior-anterior direction of the tibial coordinate system is defined as the direction perpendicular to both the defined superior-inferior and medial-lateral directions.

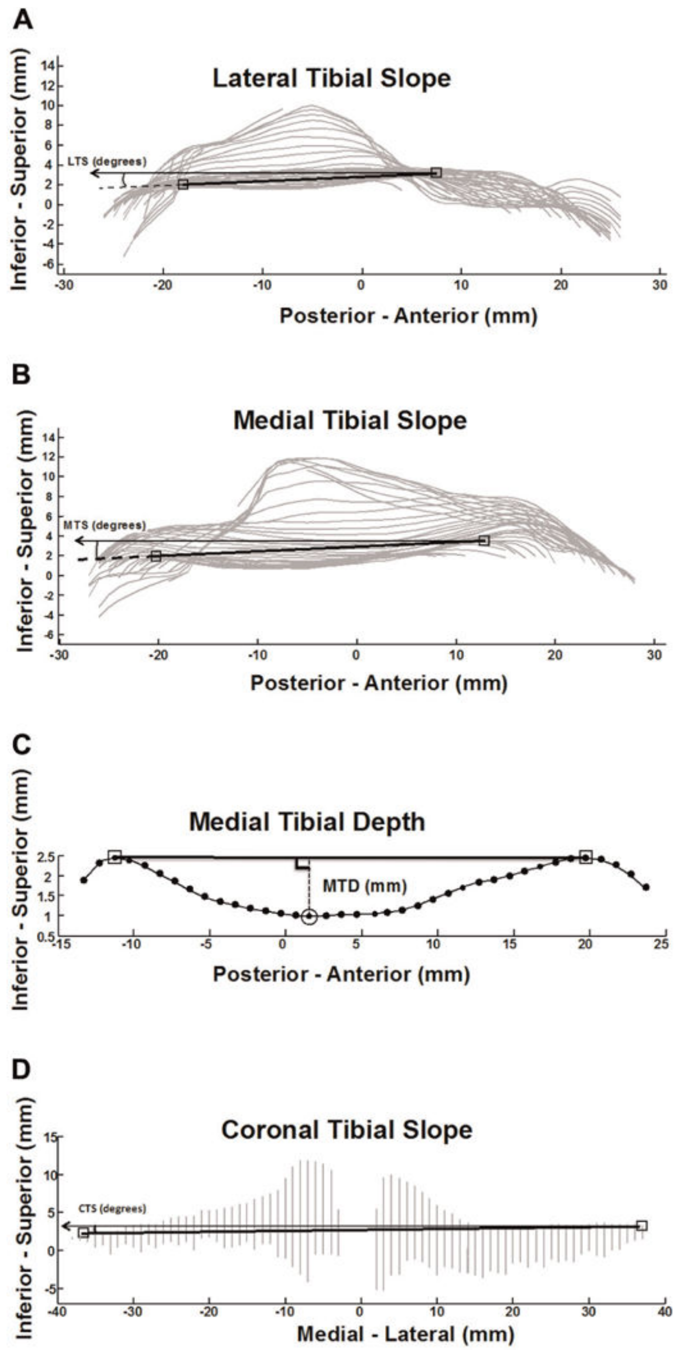

Figure 2.

(A, B) The lateral and medial tibial slopes (LTS and MTS) are defined as the slope of the lines between the anterior and posterior peaks (black open squares) of the lateral and medial tibial compartments, respectively, relative to the line perpendicular to the tibial inferior-superior axis in the posterior direction. Negative LTS and MTS angles indicate a posteriorsuperior directed slope of the plateau, and positive angles (as shown in A and B) represent a posterior-inferior directed slope. A value of 0 indicates the LTS and MTS are perpendicular to the inferior-superior axis of the tibia. (C) The medial tibial depth is defined as the greatest depth of concavity measured perpendicular from the line between the anterior and posterior peaks in the medial compartment (vertical axis scaled up). (D) The coronal tibial slope is defined as the slope of the line connecting the most medial and lateral peaks of the tibial plateau relative to the line perpendicular to the tibial long axis in the lateral direction (medial-lateral axis).

TABLE 1

Participant Demographics[a]

Participants	ACL Injured		Control	
	Mean (SD)	Range	Mean (SD)	Range
Males and females				
No.	88		88	
Age, y	17.35 (2.33)	13–23	17.41 (2.47)	12–24
Height, cm	171.28 (9.38)	152.4–208.28	171.19 (9.46)	152.4–203.2
Weight, kg	70.37 (14.51)	50.3–124.7	68.1 (13.43)	46.3–110.7
Days between injury + MRI	23.9 (26.41)	1–110	23.9 (26.41)	1–110
Females				
No.	61		61	
Age, y	17.05 (2.22)	13–21	17.15 (2.27)	12–22
Height, cm	167.63 (7.23)	152.4–185.42	167.88 (7.63)	152.4–186.055
Weight, kg	66 (9.84)	50.3–90.7	63.52 (10.01)	46.3–85.3
Days between injury + MRI	24.59 (26.51)	1–110	24.59 (26.51)	1–110
Males				
No.	27		27	
Age, y	18.04 (2.47)	14–23	18 (2.81)	14–24
Height, cm	179.52 (8.51)	167.64–208.28	178.67 (9.01)	154.94–203.2
Weight, kg	80.23 (18.31)	54.4–124.7	78.43 (14.56)	51.71–110.7
Days between injury + MRI	22.33 (26.61)	1–103	22.33 (26.61)	1–103

[a]For controls, the time interval between ACL injury and MRI was the same as the ACL-injured athletes because both groups (ACL injured and control) underwent MRI acquisition on the same day. ACL, anterior cruciate ligament; MRI, magnetic resonance imaging.

TABLE 2

Comparison of the Injured vs Uninjured Knees of the ACL-Injured Participants

Group: Variable	Knee, Mean (SD) Injured	Knee, Mean (SD) Uninjured	*P* Value
Males and females			
LTS, deg	−1.7 (3.1)	−1.9 (3.6)	.377
MTS, deg	−3.5 (2.7)	−3.7 (2.7)	.313
CTS, deg	1.5 (1.5)	1.0 (1.7)	.009
MTD, mm	1.3 (0.5)	1.3 (.5)	.157
Females			
LTS, deg	−1.2 (3.1)	−1.1 (3.6)	.700
MTS, deg	−3.0 (2.8)	−3.3 (2.7)	.334
CTS, deg	1.4 (1.6)	0.9 (1.8)	.036
MTD, mm	1.2 (0.5)	1.3 (.4)	.078
Males			
LTS, deg	−2.7 (2.9)	−3.8 (3.1)	.006
MTS, deg	−4.4 (2.1)	−4.5 (2.6)	.734
CTS, deg	1.8 (1.4)	1.4 (1.3)	.120
MTD, mm	1.4 (0.5)	1.4 (.6)	.789

[a]Findings from paired *t*-test analyses of subchondral bone measurements made in the tibia coordinate system. CTS, coronal tibial slope; LTS, lateral tibial plateau slope; MTD, depth of the medial tibial plateau; MTS, medial tibial plateau slopes.

TABLE 3

Measurements of the Subchondral Bone Portion of the Tibial Plateau[a]

Variable: Group	All (n = 88)	Males (n = 27)	Females (n = 61)
LTS, deg			
ACL	−1.9 ± 3.6	−3.8 ± 3.1	−1.1 ± 3.6
Control	−3.3 ± 3.1	−3.6 ± 2.8	−3.2 ± 3.3
MTS, deg			
ACL	−3.7 ± 2.7	−4.5 ± 2.6	−3.3 ± 2.7
Control	−3.9± 3.2	−4.2 ± 2.8	−3.7 ± 3.4
CTS, deg			
ACL	1.1 ± 1.7	1.4 ± 1.3	0.9 ± 1.8
Control	0.9 ± 1.8	1.3 ± 1.7	0.7 ± 1.9
MTD, mm			
ACL	1.3 ± 0.5	1.4 ± 0.6	1.3 ± 0.4
Control	1.4 ± 0.6	1.4 ± 0.6	1.3 ± 0.6

[a]Data from the uninjured knees of the ACL-injured athletes and the corresponding sides of the controls. Values in mean ± SD. ACL, anterior cruciate ligament; CTS, coronal tibial slope; LTS, lateral tibial plateau slope; MTS, medial tibial plateau slope; MTD, depth of the medial tibial plateau.

TABLE 4

Univariate Associations Between Measurements of Subchondral Bone Geometry Made in the Tibial Coordinate System and Risk of a First Noncontact ACL Injury

Group: Variable	*P* Value	Odds Ratio	95% CI	Coefficient	SE
Males and females					
LTS, deg	**.008**	**1.146**	**1.037, 1.268**	**0.137**	**0.051**
MTS, deg	.652	1.025	0.92, 1.143	0.025	0.055
CTS, deg	.33	1.099	0.909, 1.33	0.095	0.097
MTD, mm	.642	0.876	0.502, 1.531	−0.132	0.285
Females					
LTS, deg	**.003**	**1.217**	**1.067, 1.386**	**0.196**	**0.067**
MTS, deg	.415	1.055	0.927, 1.201	0.054	0.066
CTS, deg	.37	1.113	0.881, 1.407	0.107	0.12
MTD, mm	.625	0.833	0.4, 1.734	−0.183	0.374
Males					
LTS, deg	.871	0.985	0.816, 1.188	−0.016	0.096
MTS, deg	.65	0.954	0.777, 1.17	−0.047	0.104
CTS, deg	.674	1.073	0.774, 1.487	0.07	0.167
MTD, mm	.887	0.94	0.398, 2.219	−0.062	0.439

[a]Results from conditional logistic regression analysis of data obtained from the uninjured knees of the ACL-injured athletes and the corresponding sides of the matched controls. Comparisons are for the subchondral bone measurement of the LTS, MTS, CTS, and MTD. Boldface indicates statistical significance. ACL, anterior cruciate ligament; CI, confidence interval; CTS, coronal tibial slope; LTS, lateral tibial plateau slope; MTD, depth of the medial tibial plateau; MTS, medial tibial plateau slope.

TABLE 5.

Multivariate Associations Between Measurements of Subchondral Bone Geometry Made in the Tibial Coordinate System and Risk of a First-Time Noncontact ACL Injury

Group: Variable	*P* Value	Odds Ratio	95% CI	Coefficient	SE
Males and females					
LTS, deg	**.007**	**1.184**	**1.048, 1.337**	**0.169**	**0.062**
MTS, deg	.235	0.922	0.806, 1.054	−0.081	0.068
CTS, deg	.717	1.04	0.842, 1.284	0.039	0.108
MTD, mm	.784	0.921	0.512, 1.656	−0.082	0.299
Females					
LTS, deg	**.002**	**1.319**	**1.106, 1.572**	**0.277**	**0.09**
MTS, deg	.111	0.861	0.717, 1.035	−0.149	0.094
CTS, deg	.775	1.046	0.791, 1.383	0.045	0.143
MTD, mm	.54	0.771	0.335, 1.772	−0.26	0.425
Males					
LTS, deg	.755	0.966	0.78, 1.197	−0.034	0.109
MTS, deg	.601	0.942	0.753, 1.178	−0.06	0.114
CTS, deg	.52	1.132	0.776, 1.65	0.124	0.192
MTD, mm	.96	0.977	0.398, 2.398	−0.023	0.458

[a] Results from conditional logistic regression analysis of data obtained from the uninjured knees of the ACL-injured athletes and the corresponding sides of the matched controls. Comparisons are for the subchondral bone measurement of the LTS, MTS, CTS, and MTD. Boldface indicates statistical significance. ACL, anterior cruciate ligament; CI, confidence interval; CTS, coronal tibial slope; LTS, lateral tibial plateau slope; MTD, depth of the medial tibial plateau; MTS, medial tibial plateau slope.