Geometric profile of the tibial plateau cartilage surface is associated with the risk of non-contact anterior cruciate ligament injury

By: Bruce D. Beynnon, Pamela M. Vacek, Daniel R. Sturnick, Leigh Ann Holterman, Mack Gardner-Morse, Timothy W. Tourville, Helen C. Smith, James R. Slauterbeck, Robert J. Johnson, and Sandra J. Shultz

Beynnon, B. D., Vacek, P. M., Sturnick, D. R., Holterman, L. A., Gardner-Morse, M., Tourville, T. W., Smith, H. C., Slauterbeck, J. R., Johnson, R. J. and Shultz, S. J. (2014), Geometric profile of the tibial plateau cartilage surface is associated with the risk of non-contact anterior cruciate ligament injury. J. Orthop. Res., 32: 61–68. doi: 10.1002/jor.22434

Abstract:

The purpose of this study was to determine if geometry of the articular surfaces of the tibial plateau is associated with non-contact anterior cruciate ligament (ACL) injury. This was a longitudinal cohort study with a nested case–control analysis. Seventy-eight subjects who suffered a non-contact ACL tear and a corresponding number of controls matched by age, sex, and sport underwent 3 T MRI of both knees. Surface geometry of the tibial articular cartilage was characterized with polynomial equations and comparisons were made between knees on the same person and between ACL-injured and control subjects. There was no difference in surface geometry between the knees of the control subjects. In contrast, there were significant differences in the surface geometry between the injured and normal knees of the ACL-injured subjects, suggesting that the ACL injury changed the cartilage surface profile. Therefore, comparisons were made between the uninjured knees of the ACL-injured subjects and the corresponding knees of their matched controls and this revealed significant differences in the surface geometry for the medial ($p < 0.006$) and lateral ($p < 0.001$) compartments. ACL-injured subjects tended to demonstrate a posterior–inferior directed orientation of the articular surface relative to the long axis of the tibia, while the control subjects were more likely to show a posterior–superior directed orientation.

Keywords: anterior cruciate ligament | knee | injury mechanisms | joint geometry

Article:

Severe knee injury, such as an anterior cruciate ligament (ACL) disruption, is often immediately disabling and has been associated with the early onset of post-traumatic osteoarthritis regardless of whether surgical or non-surgical treatment is chosen.[1, 2] This has motivated studies that have focused on identifying the variables associated with increased risk of ACL injury, so that prevention strategies can be developed and those at increased risk can be identified and targeted for intervention.[3]

During the process of suffering an ACL injury, the geometry of the articular surfaces of the knee is important in controlling the biomechanical response of the tibiofemoral joint and ACL.[4, 5] For example, there appears to be a consensus forming in the literature that individuals who are at increased risk of suffering non-contact ACL disruptions have increased posterior–inferior directed slopes of the subchondral bone portion of their tibial plateaus compared to uninjured controls.[6-16] This relationship is important because the magnitude of ACL strain values produced by impulsive loading of the knee during common sports-related movements such as jump landings are directly related to the posterior–inferior directed slope of the subchondral bone of the proximal tibia.[4, 17, 18]

Most of what is known about the relationship between the risk of suffering non-contact ACL injury and joint geometry has come from studies of the underlying subchondral bone of the tibia plateau; however, the large inter-segmental forces that are transmitted between the femur and tibia occur across the surface of the articular cartilage.[16] Very little is known about the relationship between geometry of the surface of articular cartilage and the risk of suffering non-contact ACL injury. It is important to understand this relationship because the thickness of articular cartilage about the tibial plateau is not uniform and the three dimensional geometry of its surface is very different than the geometry of the underlying subchondral bone.[19] Therefore, cartilage and bone may have independent effects on the risk of non-contact ACL injury.

The objective of this study was to determine the association between the geometry of the surface of articular cartilage about the tibial plateau and the risk of suffering non-contact ACL injury. We hypothesized that individuals who are at increased risk of suffering non-contact ACL injury have different surface geometry of the articular cartilage of the tibia plateau in comparison to those at lower risk.

METHODS

The investigation was approved by our institutional review board and all subjects provided written informed consent prior to data collection. Subjects were selected from an ongoing prospective cohort study with a nested, matched case–control analysis that was designed to identify the combination of risk factors associated with non-contact ACL injury. Sport teams from 18 high schools (and the affiliated middle schools) and 8 colleges were monitored at the start of the fall 2008 sports season and as the study progressed 10 high schools were added, creating a total of 28 high schools and 8 colleges whose teams were monitored through the end of the winter 2012 season. The recruitment protocol was designed to identify and enroll study subjects after the ACL injury via direct contact with those providing medical coverage and care to the participating sport teams. When a non-contact ACL injury was suspected, the medical specialist notified the study coordinator who then contacted the subject and issued an invitation to participate in the study. To be included in the study, cases had to have suffered their first non-contact ACL injury (defined as an injury that did not involve a direct impact to the knee joint) during participation in an organized sport at the middle school, high school, or college level, and have no history of ACL tear on either leg. ACL disruption was diagnosed by an orthopedic surgeon and this was subsequently confirmed by MRI and arthroscopic visualization at the time of ACL reconstruction. At the same time, a control subject of the same age and sex was randomly selected from the injured subjects sports team and invited to participate, which ensured a similar exposure to the sport activity associated with the injury. Subjects with a prior ACL tear were not eligible to be selected as controls.

There were a total of 78 ACL-injured subjects and 78 matched controls (48 males and 108 females). The mean time interval between the non-contact ACL injury and acquisition of the MRI scan was 22.8 days (range 1–110 days) and was similar for male and female subjects (Table 1). Data on subject age, height, and weight are summarized in Table 1. Following enrollment, subjects underwent bilateral MRI scans with knees in full extension by a licensed MRI/radiographic technologist using the same Phillips Achievea 3.0 T MRI system (Phillips Medical Systems, Best, The Netherlands). Three-dimensional Fast Field Echo T1-weighted sagittal scans of both knees were obtained with a slice thickness of 1.2 mm and pixel size of 0.3 mm. The DICOM images were viewed and segmented on a Cintiq 21UX digitizing tablet (Wacom Technology Corporation, Vancouver, WA) using OsiriX software (Pixmeo, Geneva, Switzerland, version 3.6.1). The MRI data were acquired in three dimensions using a standardized approach which was defined by a coordinate system that was located relative to the MRI scanner. These data were transferred to a coordinate system that was located in the tibia in order to characterize the geometric profile of the articular surfaces in a reproducible and reliable manner within and between subjects (Supplement 1 and Fig. 1).

Table 1. Subject Demographics

	ACL-Injured Subjects, Mean (SD)/Min–Max	Control Subjects, Mean (SD)/Min–Max
Males and females combined		
Number (*N*)	78	78
Age (years)	17.4 (2.4)/13.0–23.0	17.4 (2.4)/12.0–24.0
Weight (kg)	70.2 (13.6)/53.1–121.1	68.2 (13.3)/46.3–110.7
Height (cm)	171.2 (9.5)/152.4–208.3	171.2 (9.7)/152.4–203.2
Time between injury and MRI (days)	22.8 (23.9)/1–110	NA
Males		
Number (*N*)	24	24
Age (years)	18.0 (2.6)/14.0–23.0	17.8 (2.5)/14.0–24.0
Weight (kg)	78.5 (16.9)/54.4–121.1	78.2 (14.0)/51.7–110.7
Height (cm)	179.4 (8.8)/167.6–208.3	179.0 (9.2)/154.9–203.2
Time between injury and MRI (days)	18.6 (21.5)/3–103	NA
Females		
Number (*N*)	54	54
Age (years)	17.2 (2.3)/13.0–21.0	17.3 (2.4)/12.0–22.0
Weight (kg)	66.5 (10.0)/53.1–90.7	63.7 (10.3)/46.3–85.3
Height (cm)	167.6 (7.3)/152.4–185.4	167.8 (7.7)/152.4–186.0
Time between injury and MRI (days)	24.7 (24.5)/1–110	NA

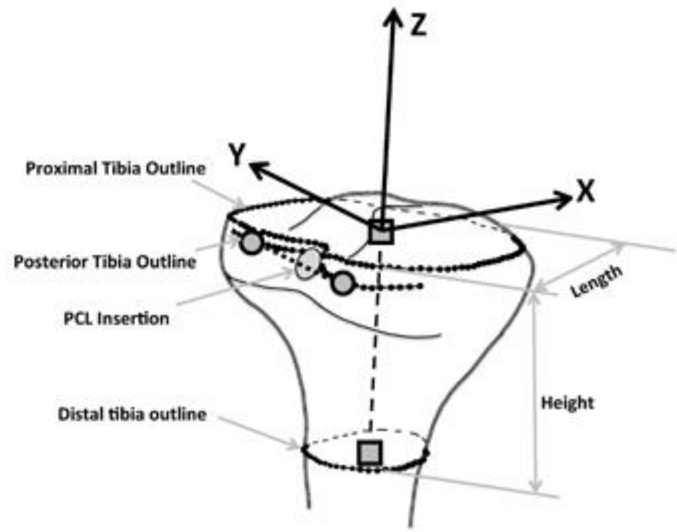

Figure 1. Segmented anatomical landmarks (black dots and lines) and tibial bony fixed coordinate system axis (arrows). The *z*-axis direction is defined by the dashed line connecting the centroids of the proximal and distal tibia cortical bone outlines (squares). The height between the distal and proximal slices is standardized to be equal to the anterior–posterior length of the proximal tibia outline. The *y*-axis direction is defined by the line connecting the posterior-most points (circles) of the posterior tibia cortical bone outline at the level of the proximal footprint of the PCL insertion on the tibia (dashed line). The *x*-axis is perpendicular to both the *y*- and *z*-axes.

The articular cartilage surfaces located in the medial and lateral compartments of the tibia plateau were segmented from the sagittal plane MRI images. Segmentation was bound by the outer boarders of the menisci and the walls of the femoral inter-condylar notch (Supplement 2). Custom MATLAB code was written to post-process the articular cartilage surface data points in order to align the data with the parasagittal (or *x*–*z*) planes in the tibia-based coordinate system. Linear interpolation of the surface data was used to generate the parasagittal (*x*–*z*) plane data at 1 mm intervals along the *x*-axis (anterior–posterior direction) with the planes 1 mm apart in a medial–lateral direction.

In an effort to identify the location where the tibial and femoral articular cartilage demonstrated maximal contact, we initially focused on the portion of the tibial articular cartilage that was in contact with the femoral articular cartilage in the regions that were not covered by the menisci. These regions had areas of concavity in both the medial and lateral compartments of the tibia. They were used in our analysis because the articular cartilage of the tibia and femur were in direct contact, and the geometry of the tibial and femoral articular surfaces followed the same profile and demonstrated maximum conformity. This study expanded on earlier one-dimensional analysis of the posterior directed slope of the subchondral bone portion of the tibial plateau [7, 8] by analysis of articular surface profiles that were aligned in the *x*–*z*, or a parasagittal, plane. The depth of concavity of the articular surface was determined in each parasagittal (*x*–*z*) plane (Fig.2A). The planes that demonstrated the greatest depth of concavity were then selected from the medial and lateral compartments (Fig. 2B).

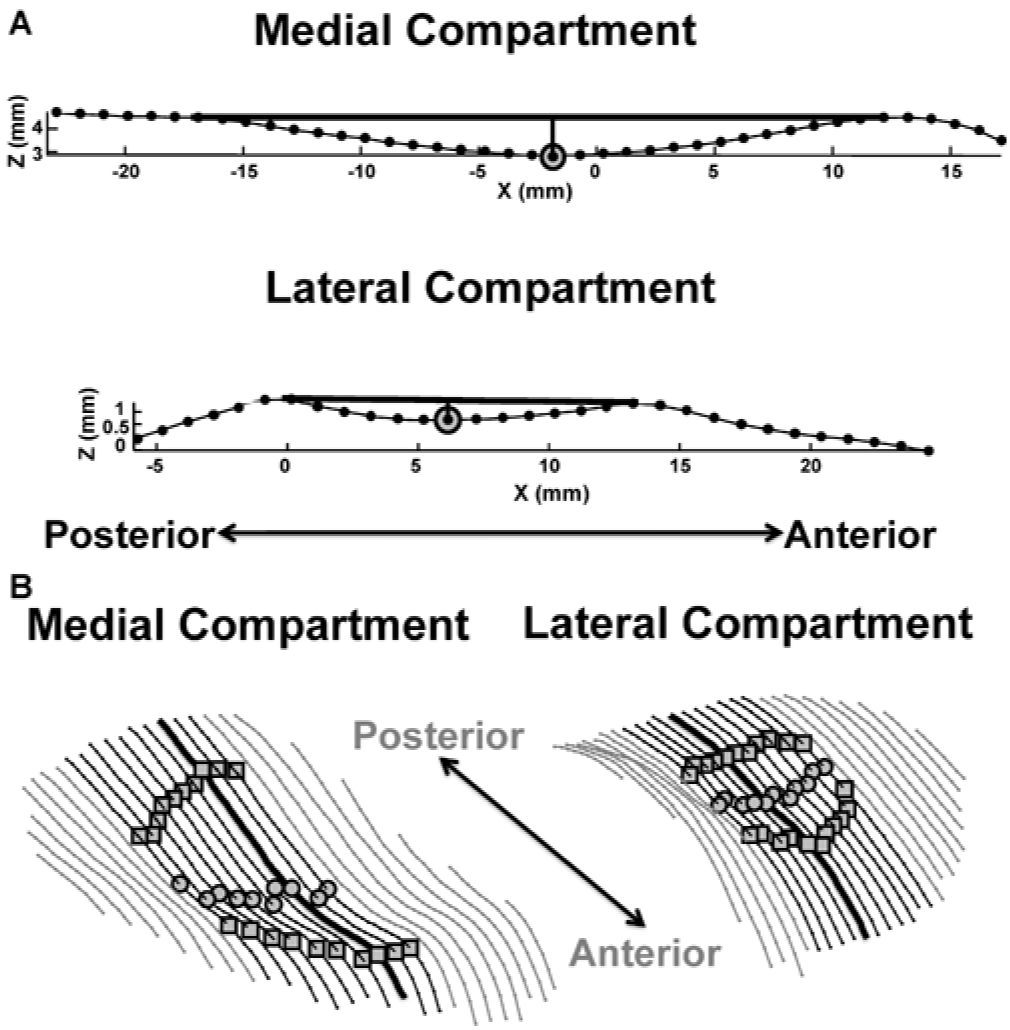

Figure 2. (A) Sagittal slice depth of concavity in the medial compartment (above) and lateral compartment (below): depth of concavity was defined as the greatest perpendicular distance (vertical line) between the articular cartilage surface (dots) and the line constructed tangent (horizontal line) to both peaks of tibiofemoral surface congruency along the articular surface. (B) Within the central region of the sagittal slices (black lines), local maxima (squares) and minima (circles) are shown on articular cartilage surface plots of a typical medial (left) and lateral compartment (right) of the tibial plateau. The geometry of the slices with the greatest depth of concavity (thick black line) was analyzed using fifth-ordered polynomials.

Statistical Analysis

A subject's articular cartilage height (*z*) was modeled as a function of the posterior–anterior distance (*x*) along the plateau of the selected articular cartilage profile using a fifth-order polynomial:

$$z = a_1x + a_2x^2 + a_3x^3 + a_4x^4 + a_5x^5$$

No intercept term was included because the mean articular cartilage height over a subject's profile was subtracted from the cartilage heights. A fifth-order polynomial was used because initial regression analyses indicated that it provided a good fit to the data and the addition of higher-order terms did not significantly reduce residual error. In addition, the articular cartilage profile was modeled as a polynomial rather than a nonlinear function so that hierarchical mixed linear models could be used to fit the articular cartilage surface data and compare knee geometry between legs on the same person and between cases and controls. In the mixed models, the anterior–posterior distance (x) was a fixed effect, while variation in the regression coefficients between individuals and deviations between the estimated and observed data points within the individuals were modeled as random effects. Interaction terms were included in the model as fixed effects to permit the regression coefficients to vary in a systematic manner between legs and between cases and controls. Model parameters were estimated by maximum likelihood and the difference in the fit of models with and without the interaction terms was assessed by the likelihood ratio test to determine the significance of differences in the polynomials used to characterize the articular surfaces that were compared (Supplement 3 presents comparisons).

Previous work has demonstrated that tibiofemoral articular cartilage may undergo substantial thickness changes (as measured with weight-bearing, fluoroscopy-assisted radiographic measurement techniques) following an ACL disruption.[20] Therefore, our first step was to gain insight into whether or not the ACL trauma modified the surface profile of the articular cartilage. This was evaluated by making side-to-side comparisons of the polynomial equations that characterized the articular surfaces of control subjects that had not suffered joint trauma in an effort to confirm that the knees demonstrated symmetric geometry. Comparisons of the polynomial fits to the articular surfaces of the ACL-injured subjects, determined as injured-to-uninjured knee comparisons, were then performed to assess whether the knees demonstrated differences that may have been produced by the ACL trauma and the initial healing response. We then proceeded to compare the uninjured knee of the cases with the corresponding knee of the matched controls. These case–control comparisons were performed using data from all subjects, as well as separately for males and females.

RESULTS

Comparison of the Side-to-Side Differences in the Articular Surface Profiles of the ACL-Injured and Control Subjects (Supplement 3, Comparisons A and B)

Among ACL-injured subjects, comparison of the polynomials for the articular cartilage surfaces of the injured and uninjured knees revealed significant differences for both the medial and lateral compartments (both $p < 0.001$). For the medial compartment, the polynomials of the injured knee tended to be less concave and flatter along the posterior region of the articular surface compared with the uninjured side. On the lateral side the injured knee tended to have an increased posterior–inferior orientation of the profile relative to the long axis of the tibia in comparison to the uninjured side. Corresponding comparisons in the control subjects (injured vs. uninjured knee as defined by the injury to the matched case) showed no significant differences in either the medial or lateral compartments ($p = 0.761$ and $p = 0.935$, respectively).

Comparison of the Articular Surface Profiles Between the ACL-Injured and Control Subjects (Supplement 3, Comparison D)

In light of the above results showing significant differences in articular surface profiles between the injured and contralateral knee of the ACL-injured subjects but no differences between the corresponding knees of the control subjects, we concluded that the ACL injury and subsequent healing response may have produced changes to the geometry of the articular surfaces of the medial and lateral compartments. Consequently, we evaluated the primary study objective by comparing the uninjured knees of the ACL-injured cases with the corresponding knees of the matched controls.

When data from both males and females were analyzed together, significant differences in the polynomials that characterized the articular surface geometry of the medial ($p < 0.006$) and lateral ($p < 0.001$) compartments of the tibia plateau were found between the un-injured knee of the injured subjects and the corresponding side of the controls (Fig. 3 and Table 2). For the lateral compartment, ACL-injured subjects tended to demonstrate a posterior–inferior directed orientation of the articular surface geometry relative to the long axis of the tibia, while the control subjects were more likely to show a posterior–superior directed orientation of articular surface geometry relative to the same axis. The significant difference in the medial compartment was not as visually apparent in the average articular surface geometry between the two groups.

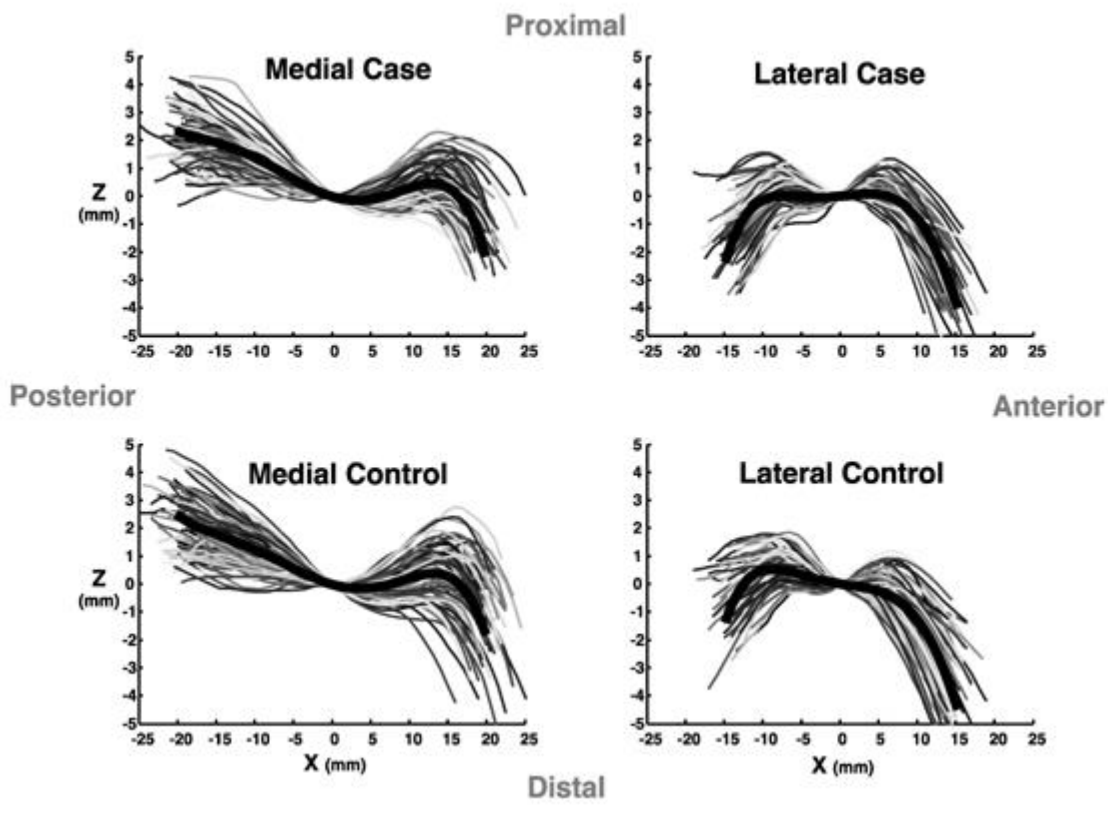

Figure 3. Tibia articular cartilage profile plots of sagittal slice that includes the maximum depth of concavity of the uninjured knees of case subjects (top views) and corresopnding knees of the

control subjects (bottom views) for the medial (left) and lateral (right) compartments. The anatomical directions of the axes are labeled. The vertical axises (z) are aligned with the long axis of the tibia and the horizonal axis is aligned in the anterior–posterior direction of the tibia. The vertical scale is not the same as the horizontal scale. Mean polynomial profiles are shown in black.

Table 2. Comparison of the Polynomial Equation Coefficients (a_1–a_5) Used to Characterize the Articular Surface Geometry Between Cases and Controls When Considering Males and Females as a Combined Group, Males as a Group, and Then Females as a Group

Group	Compartment	Status	a_1, 10^{-2}	a_2, $10^{-3}\,\text{mm}^{-1}$	a_3, $10^{-4}\,\text{mm}^{-2}$	a_4, $10^{-5}\,\text{mm}^{-3}$	a_5, $10^{-6}\,\text{mm}^{-4}$	p-Value
M and F	Lateral	Case	2.831	2.497	−8.876	−7.425	2.3076	$p<0.001$
	Lateral	Control	−4.277	2.607	−6.891	−6.954	1.855	
	Lateral	% Diff	−166.2	−4.2	28.8	6.8	24.4	
M and F	Medial	Case	−8.674	11.063	4.2129	−2.703	−1.217	$p<0.006$
	Medial	Control	−8.116	9.463	3.975	−2.148	−1.164	
	Medial	% Diff	6.9	16.9	5.9	25.8	4.6	
Males	Lateral	Case	0.3	3.159	−6.178	−6.188	1.254	$p=0.261$
	Lateral	Control	−0.974	4.119	−7.395	−5.582	1.726	
	Lateral	% Diff	−130.8	−23.3	−16.5	10.9	−27.3	
Males	Medial	Case	−10.136	10.176	4.1238	−2.215	−1.012	$p=0.369$
	Medial	Control	−8.824	8.372	3.872	−1.639	−0.929	
	Medial	% Diff	14.9	21.5	6.5	35.1	8.9	
Females	Lateral	Case	4.057	2.203	−10.374	−7.971	2.939	$p<0.001$
	Lateral	Control	−5.792	1.979	−6.591	−7.606	1.899	
	Lateral	% Diff	−170.0	11.3	57.4	4.8	54.8	
Females	Medial	Case	−8.008	11.462	4.2237	−2.924	−1.298	$p<0.025$
	Medial	Control	−7.811	9.948	4.038	−2.375	−1.274	
	Medial	%Diff	2.5	15.2	4.6	23.1	1.9	

Data are from the uninjured knee of the ACL injured subjects and the corresponding side of the controls.

When females were analyzed separately, there were significant differences in the polynomials that characterized the articular surface geometry of the medial ($p < 0.025$) and lateral ($p < 0.001$) compartments of the tibia plateau between the un-injured knee of the cases and the corresponding side of the controls (Table 2). As with the combined analysis, the articular surface of the lateral compartment of the ACL-injured females had a posterior–inferior directed orientation while the controls were more likely to have a posterior–superior directed orientation. For the males, there were no statistically significant differences in the polynomials that characterized the articular surface geometry of the medial ($p < 0.369$) and lateral ($p < 0.261$) compartments of the tibial plateau between the un-injured knee of the cases and corresponding side of the controls (Table 2).

DISCUSSION

The stress transmitted across the articular cartilage of the tibiofemoral joint during an ACL injury is dependent on many factors including the magnitude and direction of the inter-segmental forces, cartilage material properties, cartilage thickness distribution, and the geometric profile, or form, of the articular surfaces.[21] Of particular importance is the geometric profile of the articular surfaces during an injury as they guide the motion created between the tibia and femur as the ACL is loaded to failure. Previous investigations evaluating the role of these factors in non-contact ACL injury lend support to the current study. Research on the interaction between the transmission of force across the knee and risk of ACL injury has shown that an increase in the posterior–inferior directed slope of the subchondral bone portion of the tibia plateaus, relative to the longitudinal axis of the tibia, is associated with an increased risk of suffering ACL injury.[16] The current study builds on this earlier research by demonstrating that the geometry of the overlying tibial articular cartilage surfaces is associated with injury to this important structure. Significant differences in surface geometry between ACL-injured subjects and matched controls for both medial and lateral compartments were found when males and females were analyzed together and when females were analyzed separately; however, no significant differences were found when just males were analyzed.

In this study, the three-dimensional geometry of the articular cartilage surfaces of the tibia was measured in a reproducible and reliable manner, the maximum depths of concavity of the lateral and medial compartments where there was maximum conformity of the cartilage surfaces were identified, and then polynomial equations were used to characterize the profiles of the surfaces at this location. This approach allowed us to move from a one-dimensional description of the subchondral bone geometry to a two-dimensional characterization of the regions of maximum conformity of the medial and lateral articular surfaces of the tibiofemoral joint that guide load transmission across the knee.

Visual inspection of the fitted lines for the polynomials representing the articular cartilage surfaces of the medial and lateral plateaus revealed different profiles for the injured subjects compared to the controls and these were more pronounced for the lateral in comparison to the medial compartment. Comparison of the coefficients of the polynomials provides insight into this relationship. However, it is important to note that comparisons of individual coefficients of the polynomial terms must be done in the context of the values of the other terms and the portion of the anterior–posterior (or x) axis being considered. For example, as one moves away from the origin of the coordinate system, in either an anterior or posterior direction, the contribution of the linear coefficient decreases while those of the higher order coefficients increases. The polynomial expression that characterized the lateral compartment of the control subjects had a coefficient of the first-order (or linear) term that was negative (demonstrating a posterior–superior directed orientation of the lateral articular surface profile relative to the long axis of the tibia) while for the injured subjects this coefficient was positive (demonstrating a posterior–inferior directed orientation of the articular surface profile relative to the long axis of the tibia), and this differed by 166% when considering males and females as a combined group (Table 2). Comparison of the remaining coefficients associated with the second- through fifth-order terms of the polynomials for the lateral compartment between the cases and controls revealed that they were identical in sign and the percent differences were considerably smaller (Table 2). To explore the extent to which the case–control difference in the linear orientation of the lateral articular surface reflected a difference in the subchondral bone lateral tibial slope (LTS), we modeled the first-order coefficient as linear function of LTS and repeated the analysis of the lateral compartment. The first-order coefficient was significantly related the LTS ($p < 0.001$) in both males and females, and adjustment for LTS reduced the magnitude of the case–control difference in the first-order coefficients. However, the difference in the polynomials remained statistically significant for both the combined data and for females ($p < 0.001$), with the articular surface of the injured subjects' knees having a more posterior–inferior directed orientation. This finding indicates that the geometry of the articular cartilage has an influence on ACL injury risk that is independent of the effect of the slope of the underlying tibial plateau subchondral bone.

For the medial articular surfaces, comparison of the polynomial expressions between cases and controls demonstrated that the signs were identical and values of the coefficients were similar (Table 2). These results suggest that while the polynomial expressions were statistically different between the cases and controls for the medial compartment, the geometry of the articular surface of the medial compartment may have had less of an influence on the risk of suffering a non-contact ACL injury in comparison to the lateral compartment. A new theory regarding injury mechanism follows this finding. When an ACL injury occurs, the inter-segmental forces transmitted across the knee move the tibia in an anterior direction relative to the femur. It may be that individuals with reduced geometric constraint to this anterior translation are at increased risk of ACL injury compared to those with increased geometric constraint, with a more pronounced effect in the lateral compartment.

Previous research has focused on the tibial plateau subchondral bone geometry and this has introduced the hypothesis that increased posterior–inferior directed orientation of the subchondral bone of the tibial plateau relative to the long axis of the tibia, in combination with the large magnitude of the inter-segmental forces that act across the knee at the time of non-contact ACL injury, produces a coupled anterior displacement and internal rotation of the tibia about its long axis.[7, 8, 12] In addition, Lipps et al.[4] used a cadaver model to replicate a pivot landing that included flexion combined with an internal torque applied to the tibia and this revealed that the peak ACL strain values were significantly greater in females in comparison to males. This finding was attributed to females having a smaller ACL and increased LTS in comparison to males.[4] The current study supports this work through our observation of an increased posterior–inferior directed orientation of the lateral articular surface for the ACL-injured female subjects, compared to the control subjects. These findings, in combination with the fact that the axis of internal–external rotation of the tibia during flexion–extension of the knee is aligned with the long axis of the tibia and located in the medial compartment,[22] provide support for a non-contact ACL injury mechanism that involves increased anterior translation and internal rotation of the tibia relative to the femur. This coupled motion would increase ACL strain values. This is a concern when ACL injury occurs with the knee near extension, because the posterior–inferior directed slope of the subchondral portion of the tibial plateau is directly related to the landing impact-induced ACL strain values[4, 17] and the orientation of the muscles that span the joint does not allow for effective control of anterior translation and internal rotation of the tibia produced by the impulsive joint loadings that are associated with most non-contact ACL tears.

An important strength of our investigation was the use of a prospective design to identify and enroll participants immediately after they suffered their first non-contact ACL injury and the inclusion of the nested case–control component in which control subjects were randomly selected from among each case's teammates. This approach ensured that cases and controls were matched on sex, age, type of sport activity, level of play, and playing conditions, and that both cases and controls had the same opportunity to be injured. This controlled for potential confounding that could have been introduced by comparing injured and uninjured subjects that 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 articular cartilage 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 that are at the greatest risk of suffering their first non-contact ACL injury. The same definition for what constituted a non-contact ACL injury was applied to the entire cohort and consequently we knew where subjects came from in terms of the type of injury that was suffered and their injury 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 articular cartilage geometry. A limitation of the study was that it focused on geometry of the articular surface of the tibia and did not include the geometry of the meniscus. The menisci are complex structures that act in combination with the articular cartilage to transmit contact stress across the tibiofemoral joint and may have a very important role associated with ACL injury. We were also concerned that our approach characterized articular surface geometry after the injury occurred because a prospective approach that obtained pre-participation/injury MRIs would have required enrollment of over eight thousand subjects in order to generate a sample with the same number of injured subjects as in the current study.[23] The cost and time associated with this was not feasible. Consequently, our first step was to test whether the injury modified articular cartilage surface geometry by making side-to-side comparisons within cases and within controls. This revealed differences in the polynomials used to characterize articular cartilage surface geometry between the ACL-injured knee and uninjured contralateral knee in the cases, but no differences between the two knees of the control subjects. This finding indicated that the articular surface profile of the ACL-injured knee may have been altered by the injury. Therefore, we tested our primary hypothesis by comparing the surface geometry of the uninjured knee of the ACL-injured subjects with the corresponding knee of their matched controls. We found geometry of the tibial articular surface was significantly associated with risk of suffering ACL injury for the females but not the males, which may have been due to the smaller sample size for the males. Review of the average profiles of the articular surfaces suggests that case–control differences in males were similar in profile to females but were less pronounced and consequently, it may be that geometry of the lateral compartment of the tibia is only a risk factor for females and not males. This is a concern when considered in combination with the work of Lipps et al.[4, 5] that demonstrated similar changes in geometry of the lateral tibial plateau were significant predictors of peak ACL strain values and that these values were far greater in females compared to males during a simulated pivot landing.

We believe it is reasonable to assume that our MRI measures approximate articular surface shape at the time of injury as experimental studies demonstrate minimal deformations of articular cartilage are associated with other loading conditions that challenge the knee. For example, studies have shown a 7% decrease in overall cartilage volume under repeated high impact loading[24] and a 2.7% decrease in cartilage thickness after 45 min of static loading.[25] The small changes of cartilage geometry in response to these types of loads suggest that there are only minimal changes in the geometric profile of cartilage during an ACL injury and support the use of polynomials to characterize articular cartilage. Similarly, in response to diurnal loading, femoral articular cartilage thickness decreases no more than 0.6 mm in medial and lateral compartments of the tibiofemoral joints over the course of 1 day.[26, 27] These findings suggest that the geometry of the tibial plateau that was characterized with polynomial expressions did not change appreciably during the very short-time interval over which the ACL injury was suffered.

Geometry of the articular surfaces of the tibiofemoral joint is a non-modifiable risk factor, and consequently, ACL injury prevention research should consider developing intervention programs that attenuate the impact loads transmitted across the knee. This could be done through changes in landing biomechanics, the playing surface, or footwear as suggested by Oh et al.[28, 29] in an effort to decrease the impulsive joint forces that contribute to anterior translation and internal rotation of the tibia relative to the femur. In turn, this may reduce the magnitude of strain that the ACL must resist during impulsive loading and subsequently reduce the risk of ACL injury. Future research should focus on understanding how the three-dimensional geometry of the tibial articular surface is associated with risk of injury to the ACL and whether or not it acts in combination with other risk factors such as the femoral notch and ACL geometry.[12]

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's web-site.

REFERENCES

1. Lohmander LS, Englund PM, Dahl LL, et al. 2007. The long term consequence of anterior cruciate ligament and meniscus injuries: osteoarthritis. Am J Sports Med 35:1756–1769.

2. Lohmander LS, Ostenberg A, Englund M, et al. 2004. High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. Arthritis Rheum 50:3145–3152.

3. Smith HC, Vacek P, Johnson RJ, et al. 2011. Risk factors for anterior cruciate ligament injury: a review of the literature: Part 1: neuromuscular and anatomic risk. Sports Health 4:69–78. PMID: 13016072.

4. Lipps DB, Oh YK, Ashton-Miller JA, et al. 2012. Morphologic characteristics help explain the gender differences in peak anterior cruciate ligament strain during a simulated pivot landing. Am J Sport Med 40:32–40.

5. Lipps DB, Wilson AM, Ashton-Miller JA, et al. 2012. Evaluation of different methods for measuring lateral tibial slope using magnetic resonance imaging. Am J Sport Med 40:2731–2736.

6. Bisson LJ, Gurske-DePerio J. 2010. Axial and sagittal knee geometry as a risk factor for noncontact anterior cruciate ligament tear: a case-control study. Arthroscopy 26:901–906.

7. Hashemi J, Chandrashekar N, Beynnon BD, et al. 2008. The geometry of the tibial plateau and its influence on the biomechanics of the tibiofemoral joint. J Bone Joint Surg Am 90:2724–2734.

8. Hashemi J, Chandrashekar N, Mansouri H, et al. 2010. Shallow medial tibial plateau and steep medial and lateral tibial slopes: new risk factors for ACL injuries. Am J Sports Med 38:54–62.

9. Hudek R, Fuchs B, Regenfelder F, et al. 2011. Is noncontact ACL injury associated with the posterior tibial and meniscal slope? Clin Orthop Relat Res 469:2377–2384.

10. Khan MS, Seon JK, Song EK. 2011. Risk factors for anterior cruciate ligament injury: assessment of tibial plateau anatomic variables on conventional MRI using a new combined method. Int Orthop 35:1251–1256.

11. Meister K, Talley MC, Horodyski MB, et al. 1998. Caudal slope of the tibia and its relationship to noncontact injuries to the ACL. Am J Knee Surg 11:217–219.

12. Simon RA, Everhart JS, Nagaraja HN, et al. 2010. A case-control study of anterior cruciate ligament volume, tibial plateau slopes and intercondylar notch dimensions in ACL-injured knees. J Biomech 43:1702–1707.

13. Stijak L, Herzog RF, Schai P. 2008. 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 16:112–117.

14. Todd MS, Lalliss S, Garcia E, et al. 2010. The relationship between posterior tibial slope and anterior cruciate ligament injuries. Am J Sport Med 38:63–67.

15. Vyas S, van Eck CF, Vyas N, et al. 2010. Increased medial tibial slope in teenage pediatric population with open physes and anterior cruciate ligament injuries. Knee Surg Sports Traumatol Arthrosc 19:372–377.

16. Zeng C, Cheng L, Wei J, et al. 2012. The influence of tibial plateau slopes on injury of the anterior cruciate ligament: a meta-analysis. Knee Surg Sports Trammatol Arthrosc [Online] 11.

17. McLean SG, Oh YK, Plamer ML, et al. 2011. The relationship between anterior tibial acceleration, tibial slope, and ACL strain during a simulated jump landing task. J Bone Joint Surg 93:1310–1317.

18. Araki D, Thorhauer E, Tashman S. 2013. Correlation between posterior-tibial slope and in-vivo knee kinematics. Orthop Res Soc.

19. Ateshian GA, Soslowsk LJ, Mow VC. 1991. Quantitation and articular surface topography and cartilage thickness in knee joints using stereophotogrammetry. J Biomech 24:761–775.

20. Tourville TW, Johnson RJ, Slauterbeck JR, et al. 2013. Assessment of early tibiofemoral joint space width changes after anterior cruciate ligament injury and reconstruction: a matched case-control study. Am J Sport Med 41:769–778.

21. Mow VC, Huiskes R. 2005. Basic orthopaedic biomechanics and mechano-biology, 3rd ed. Chapter 2, Analysis of muscle and joint loads. Philadelphia, PA: Lipincott Williams and Wilkins.

22. Churchill DL, Incavo SJ, Johnson CC, et al. 1998. The transepicondylar axis approximates the optimal flexion axis of the knee. Clin Orthop Relat Res 356:111–118.

23. Smith HC, Johnson RJ, Shultz SJ, et al. 2012. A prospective evaluation of the Landing Error Scoring System (LESS) as a screening tool for anterior cruciate ligament injury risk. Am J Sports Med 40:52–56.

24. Eckstein F, Lemberger B, Gratzke C, et al. 2005. In vivo cartilage deformation after different types of activity and its dependence on physical training status. Ann Rheum Dis 64:291–295.

25. Catofana S, Eckstein F, Wirth W, et al. 2011. In vivo measures of cartilage deformation: patterns in healthy and osteoarthritic female knees using 3T MR imaging. Eur Radiol 21:1127–1135.

26. Waterton JC, Solloway S, Foster JE, et al. 2000. Diurnal variation in the femoral articular cartilage of the knee in young adult humans. Magn Reson Med 43:126–132.

27. Coleman JL, Windmyer MR, Leddy HA, et al. 2013. Diurnal variations in articular cartilage thickness and strain in the human knee. J Biomech 46:541–547.

28. Oh YK, Kreinbring JL, Wojtys EM, et al. 2012. Effect of axial tibial torque on ACL relative strain and strain rate in an in-vitro simulated pivot landing. J Orthop Res 30:528–534.

29. Oh YK, Lipps DB, Ashton-Miller JA, et al. 2012. What strains the anterior cruciate ligament during a pivot landing. Am J Sports Med 40:574–583.