The Geometry of the Articular Cartilage of the Tibial Plateau and Anterior Cruciate Ligament Injury Risk

INTRODUCTION

Injuries to the Anterior Cruciate Ligament (ACL) of the knee are common and can lead to early onset of posttraumatic osteoarthritis (PTOA).\(^1\) The geometry of the subchondral bone of the tibial plateau plays an important role in controlling the transmission of intersegmental forces across the knee during weight-bearing activity and is related to the risk of suffering ACL injury. In case-control studies, injured subjects were found to have steeper posterior-directed lateral and medial tibial plateau slopes, and a shallower medial tibial plateau depth than matched controls.\(^2,3,4,5,6\) An increase in the posterior-directed slope of the plateau is associated with an increase in the magnitude of the anterior-directed shear force that is associated with the large compressive loads generated by bodyweight and muscle contraction during activities such as landing from a jump—a common mechanism for injury to the ACL.

While geometry of the subchondral bone surface of the tibial plateau has received significant attention, a review of the literature reveals no studies of the influence of the geometry of the tibial articular cartilage on the risk of ACL injury. The primary goal of this study was to test the hypothesis that the tibial plateau articular cartilage geometry is associated with risk of ACL injury.

METHODS

The study used a matched case-control design, approved by the IRB at the University of Vermont. Case subjects were eligible for recruitment if they were between the ages of 12-24, played on a sports team affiliated with their middle school, high school, or college, and suffered a non-contact ACL injury. Control subjects were drawn from the same team and matched by age, sex, and exposure. 60 subjects (30 cases and 30 controls) were recruited and provided informed consent for this study. Using a Phillips Achieva 3.0T MRI system (Fletcher Allen Healthcare, Burlington, VT), T1-weighted sagittal scans of the tibiofemoral joint were acquired. The DICOM images were viewed and digitized using OsiriX software (Pixmeo, version 3.6.1) and a Cintiq 21UX digitizing tablet (Wacom, 2010). The articular and lateral compartments of the tibial plateau were segmented in the sagittal view. Using Matlab software, data points were put in a standardized and reproducible coordinate system aligned within the tibia. In the medial compartment, the cartilage profile on the sagittal slice that contained the deepest point of concavity was assumed to represent the region of maximum conformity with the femoral condyle, and was selected for analysis. In the lateral compartment, a small concavity in the articular surface was evident, which was assumed to represent the region of maximum conformity with the lateral femoral condyle. The slice that contained the deepest point of this region was also selected for analysis. A hierarchical mixed model was used to estimate the average of the cartilage profiles by fitting a 4th order polynomial to the selected slices from 30 cases and 30 controls. Interaction terms were included in the model as fixed effects to permit the regression coefficients to vary between cases and controls. Variation in the coefficients between individuals and deviations between the estimated and observed data points within individuals were modeled as random effects. 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.

RESULTS

Coefficients for the polynomial equations are presented below:

<table>
<thead>
<tr>
<th>Table 1</th>
<th>( y_{int} )</th>
<th>( x )</th>
<th>( x^2 )</th>
<th>( x^3 )</th>
<th>( x^4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medial</td>
<td>-8.78E-01</td>
<td>3.39E-02</td>
<td>8.01E-03</td>
<td>-1.16E-04</td>
<td>-1.30E-05</td>
</tr>
<tr>
<td>Control</td>
<td>-5.21E-01</td>
<td>1.70E-02</td>
<td>7.24E-03</td>
<td>-1.20E-04</td>
<td>-1.00E-05</td>
</tr>
<tr>
<td>Lateral</td>
<td>9.59E-01</td>
<td>2.89E-02</td>
<td>-2.57E-03</td>
<td>-6.00E-05</td>
<td>-4.36E-05</td>
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<tr>
<td>Control</td>
<td>5.81E-01</td>
<td>4.19E-02</td>
<td>-2.97E-03</td>
<td>-1.20E-04</td>
<td>-4.00E-05</td>
</tr>
</tbody>
</table>

The 4th order polynomial models for both the medial and lateral tibial articular surface profiles were significantly different between cases and controls (\( p<0.001 \) for both compartments). Figure 1 shows the medial compartment cartilage profiles of the cases and controls plotted with their respective polynomial model curve fits (lateral compartment not shown).

DISCUSSION

Using 4th order polynomial models to represent an average cartilage profile of the ACL injured case subjects and uninjured matched controls, a clear difference between the two groups is evident. In the medial compartment, the polynomial representing the control subjects’ articular surface profiles shows a higher posterior elevation relative to that of the case group. In the lateral compartment, the polynomial representing the case subjects’ profile is oriented with a posterior-inferior tilt relative to that of the control group. Considering these observations in the light of the ACL injury mechanism, a compressive impulse force such as that produced by body weight when landing from a jump would be more likely to cause the femurs of case subjects to slide posteriorly off the tibial plateau, than in control subjects. Under the same force, it is conceivable that the ACLs in the injured group would be under higher strain than those of the uninjured group, putting them at an increased risk of rupturing the ACL. This assumes, however, that the injury did not cause the divergence in profiles. While the study design does not allow for an MRI to be taken both before and after the injury, conducting the same analysis using the contralateral knees of the subjects in the sample may help validate that assumption.

The divergence of shape of articular cartilage may further our understanding of how the forces transmitted across the knee influence risk of injury, how individual knee joints respond to loading, and subsequent risk of development of PTOA. The study also presents a new method of examining joint geometry by taking into consideration the entire contour of the cartilage profile, expanding on previous one-dimensional measurements of tibial plateau slope and depth of concavity.

SIGNIFICANCE

This study furthers our understanding of the physical characteristics that predispose athletes to ACL injury. It is a first step in devising a method of characterizing the complex geometry of the articular cartilage and subsequently identifying those at increased risk for ACL injury or re-injury of the same kind. Interventions can then be targeted in an effort to reduce the risk of this injury and associated sequelae.

REFERENCES


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Bruce.beynnon@uvm.edu