Knee Bone Shape Features Are Correlated With Abnormal Tibial Translation After ACL Injury And Reconstruction

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Introduction: Anterior cruciate ligament (ACL) injuries are one of the most common ligamentous injuries of the knee, mostly affecting the young and healthy population. ACL reconstruction may incompletely restore tibiofemoral mechanics, such as tibial position, anterior tibial translation, and internal tibial rotation. Recently, there has been an increased interest in understanding the role of the bone shape in tibiofemoral movements, in particular observing posterior tibial slope. However, was shown how multiple geometric measurements used for the description of a complex shape are often highly correlated and a holistic approach to modeling the shape can be more effective. Statistical Shape Modeling (SSM) is a mathematical method able to describe complex shapes in brief features vector without a-priori assumptions. In this study, 3D Magnetic Resonance Imaging (MRI) is used to study the relationships between tibia and femur shape, and the Anterior Tibial Translation in the extended position (ATT_ext) in subjects with acute ACL injuries measured at time points prior to surgery, and at 1 and 2 years after the reconstruction.

Methods: Subjects: Bilateral knees of thirty-four patients with isolated unilateral ACL injuries were scanned using a 3 Tesla MRI scanner (GE Healthcare, Milwaukee, WI, USA) with an 8-channel phased array knee coil (Invivo, Orlando, FL, USA) prior to surgical reconstruction (age = 27.85 ± 7.12 years, BMI = 23.92± 2.72 Kg/m², 12 female) and at 1 year after surgery. Ten of these patients (age = 32.56 ± 5.04 years, BMI = 23.82± 3.24 Kg/m², 5 female) were also scanned 2 years after surgery. Patients were excluded if there was a history of contralateral knee injury, pre-existing degenerative changes, a history of inflammatory arthritis, multiple ligamentous injury, or meniscal injury requiring repair.

MRI Protocol: The imaging protocol included Sagittal T2 fast spin-echo (FSE) images with TR/TE = 4000/49.3 ms, slice thickness of 1.5 mm, spacing of 1.5 mm, field of view of 16 cm, 512 x 512 matrix size and echo train length 9. The patients were scanned in the extended and flexed (~30 degrees) positions with 25% body weight applied axially.

Image Post Processing: Image processing was performed using an in-house Matlab-based program. The tibia and femur were segmented semi-automatically. The mid-point between the tibial medial and lateral posterior cortical border was defined as tibia origin. The femoral condyles were modeled as spheres. The mid-point between the center of the two spheres defined femur origin. ATT_ext was computed as the distance between the tibia and femur origins projected onto the transverse plane of the tibia in the anteroposterior direction. To compute the SSM, a set of landmarks was identified on each femur and tibia surfaces using an algorithm based on the matching of local curvature. The SSM generated 20 modes that comprised more than 90% of the entire variability seen in the bone shapes.
(T1-T20, F1-F20). Each mode describes a distinct aspect of the tibia and femur shape. The early modes describe diffuse shape features that showed large variability in the analyzed dataset, such as bone volume represented by T1 and F1, and the intercondylar notch geometry represented by F2. Later modes are related to more focused futures such as lateral tibia slope (T14) and elevation of the femoral trochlea (F19).

Statistical Analysis: A stepwise linear regression was applied to determine the mode predictors of (1) injury side ATT_ext at baseline, (2) injury side ATT_ext at 1 year, (3) side to side difference (SSD), defined as [injury side ATT_ext]-[contralateral ATT_ext], at baseline, and (4) SSD at 1 year. The side-to-side difference was used to estimate the presumed pre-injury position of the tibia for each patient based on their uninjured, contralateral knee. Femur and tibia modes were considered as possible predictors, with the threshold for the predictor selection fixed at alpha=0.05. The model was adjusted for bone size.

Second, an ad-hoc single linear regression was performed on a subset of the whole cohort that had completed the 2 year follow up (ten patients) to better investigate the role of a specific shape mode that were highly significant in the first analysis.

Results:

Table 1 shows the results of the stepwise logistic regression model. A good estimation can be identified at baseline for both the ATT_ext (R2= 0.45, p <0.001) and SSD (R2 = 0.35, p 0.05), but showed a significant correlation between baseline and 2 years (R2=0.48, p=0.027).

<table>
<thead>
<tr>
<th>Predicted Variable</th>
<th>Variables Included in the model</th>
<th>P-value</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACL knee ATT_ext Baseline</td>
<td>T14 (p &lt;0.001); T8 (p = 0.001)</td>
<td>&lt;0.001</td>
<td>0.454</td>
</tr>
<tr>
<td>SSD ATT_ext Baseline</td>
<td>T14 (p = 0.006); F19 (p = 0.030); T9 (p = 0.048)</td>
<td>&lt;0.001</td>
<td>0.3517</td>
</tr>
<tr>
<td>ACL knee ATT_ext 1 Year</td>
<td>F8 (p = 0.016); F11 (p = 0.039)</td>
<td>0.004</td>
<td>0.274</td>
</tr>
<tr>
<td>SSD ATT_ext 1 Year</td>
<td>F18 (p = 0.014); F15 (p = 0.043)</td>
<td>0.0190</td>
<td>0.24</td>
</tr>
</tbody>
</table>

Discussion: T14, primarily related to an increase in lateral slope, correlates positively with ATT_ext at baseline and 2 years, and may be associated with a higher ATT_ext. Interestingly, there is an involvement of the intercondylar eminence in this deformation (Figure 1), suggesting that the shape features that can predict ATT_ext may be more complex than the lateral tibial slope alone. Additionally, longitudinal correlation between ATT_ext at baseline and 2 year follow-up, the two points at which T14 was also highly correlated, may suggest a return of some joint laxity that was not observed at the 1 year mark. Limitation of this study is the small size of the 2 years cohort. Further investigation is warranted to confirm the findings and further explore the relationship between bony geometry and arthrokinematics in a larger cohort.

Significance: The results of this study shows that specific aspect of the bone shape can predict the Anterior Tibiae Translation at baseline and 2 years after injury. Understanding the interrelationship between the bone shape and the tibiofemoral movement may play a role in predicting long term outcome after ACL reconstruction, and possibly prevent secondary injuries.
Figure 1: T14 features in the shape model of the tibial plateau are associated with high ATT_ext at baseline and 2 year after ACL injury. Positive values (red) displacement towards superior direction, negative values (blue) displacement towards inferior direction.