MRI-based automated statistical shape modeling identifies sex-based differences in tibiofemoral morphology in patients with ACL injuries

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INTRODUCTION:

Anterior cruciate ligament (ACL) injuries are extremely common and lead to pain, disability, and increased risk of osteoarthritis. The incidence of ACL tears has risen over the past twenty years, with young athletes being one of the most at risk populations for such an injury. One discrepancy that is not well understood is the difference in tear rates between sexes. Female athletes have been found to experience ACL injuries at rates 2 to 9 times higher than their male counterpart, even after controlling for the sport played and the mechanism of injury. While anatomical, biomechanical, and hormonal factors have been proposed to explain this disparity, the role of a patient's intrinsic bone shape on ACL injury risk remains unclear. This study seeks to characterize sex-based differences in tibiofemoral bone morphology to better understand the underlying factors that contribute to the increased risk of ACL tears seen in female athletes.

METHODS: A total of 803 pre-operative clinical MRI scans were selected for statistical shape modeling from 415 female and 388 male patients (ages 12 to 63) with primary complete ACL rupture and no history of prior ACL reconstruction. Patient age was compared between male and female cohorts using an unpaired Student's t-test, which revealed no significant difference ($p = 0.6884$). Using deep convolution neural networks, sagittal proton-density-weighted MRI scans were automatically segmented to predict masks of the femur and tibia of the knee. Segmentation outputs were manually reviewed and quality controlled to ensure anatomical accuracy prior to further analysis. Three-dimensional bone shape models were generated for the tibia and femur of each patient. Statistical shape modeling was conducted using principal component analysis to derive the first twenty principal components (PCs) representing orthogonal modes of shape variation across the cohort. Mean PC scores were then compared between male and female patients using unpaired Student's t-tests to assess sex-based differences in tibiofemoral bone shape. To correct for multiple comparisons, the false discovery rate (FDR) was controlled using the two-stage step-up method of Benjamini, Krieger, and Yekutieli. Statistical significance was defined as $q < 0.05$.

RESULTS:

Of the extracted principal components, six femoral and five tibial features demonstrated statistically significant differences between female and male patients. The femur of female patients demonstrated increased lateral but decreased medial condylar width, decreased medial epicondylar width, a narrower and shallower intercondylar notch, and shallower trochlear groove (Femoral Modes 1, 2, 10, 12, 13,14). The tibia of female patients exhibited squarer shaped medial and lateral condyles that were increased in length in the anterior-posterior axis and decreased in width in the medial-lateral axis (Tibial Modes 1, 5, and 6). Female tibias also had elevated, more convex medial and lateral tibial plateaus, resulting in less prominent intercondylar tubercles (Tibial Modes 11 and 19).

DISCUSSION AND CONCLUSION:

These findings suggest that there are intrinsic sex-based differences in tibiofemoral morphology that may help explain the disproportionately high ACL tear rates experienced by females. The narrower and shallower intercondylar notch identified in female femurs is a known risk factor for ACL tears and injuries. Additionally, the decreased width of the medial condyle and epicondyle suggest an overall narrower femoral morphology, which could influence coronal plane alignment of the knee (CPAK) and load distribution during activities. A shallower femoral trochlear groove can lead to patellar instability and has also been shown to be a significant risk factor for ACL injuries. On the tibial side, the elevated and flatter tibial plateaus and less prominent intercondylar tubercles may alter ACL insertion and have been shown to increase cartilage pressure, leading to increased knee laxity. By leveraging statistical shape modeling, this study not only characterizes these sex-based differences, but also identifies specific morphological features that may serve as imaging biomarkers for ACL injury risk. This model provides a framework for early identification of at-risk individuals and could inform the development of personalized screening and prevention strategies, particularly in female athletes who remain disproportionately affected.
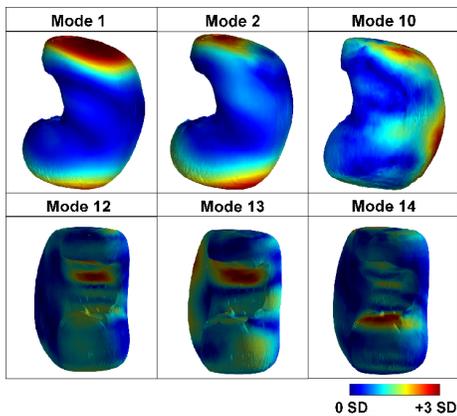
Fig 1: The significant principal component analysis (PCA) modes of the distal femur. Each mode depicts vertex displacement of ± 3 SD from the mean shape. Each three-dimensional model was positioned to highlight the prominent feature of the respective mode.
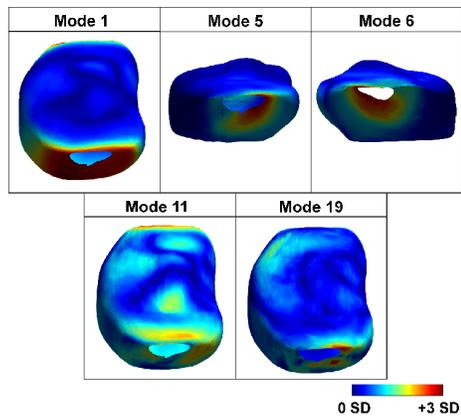

Fig 2: The significant principal component analysis (PCA) modes of the proximal tibia. Each mode depicts vertex displacement of ± 3 SD from the mean shape. Each three-dimensional model was positioned to highlight the prominent feature of the respective mode.