

# Automated statistical shape modeling identifies sex-based differences in tibial morphology of patients with primary 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 tibial 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. Following manual quality control, three-dimensional bone shape models were generated for 618 tibial scans (310 female and 308 male). 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 tibial 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, five tibial features demonstrated statistically significant differences between female and male patients. Compared to male tibias, female tibias exhibited several distinct morphological features. These included a reduced tibial eminence size (Mode 12, 16, and 19) and shallower posterior intercondylar area (Mode 9, 11, 12, 16, and 19). Female tibias also demonstrated truncated medial/ lateral condyles along the anterior-posterior axis (Modes 9 and 11) as well as reduced surface area of the medial and lateral tibial plateaus (Mode 16). Other distinguishing features included a more concave medial tibial plateau (Mode 1 and 19), elevated anterior, lateral edge of the lateral tibial plateau (Mode 11 and 19), and elevated posterior edge of the lateral condyle relative to the medial condyle (Mode 19) also defined female tibias. The first 20 principal components of the tibial shape model explain approximately 63.70% of the total variance.

**DISCUSSION:** These findings suggest that there are intrinsic sex-based differences in tibial morphology that may help explain the disproportionately high ACL tear rates experienced by females. 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.

**SIGNIFICANCE:** 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.

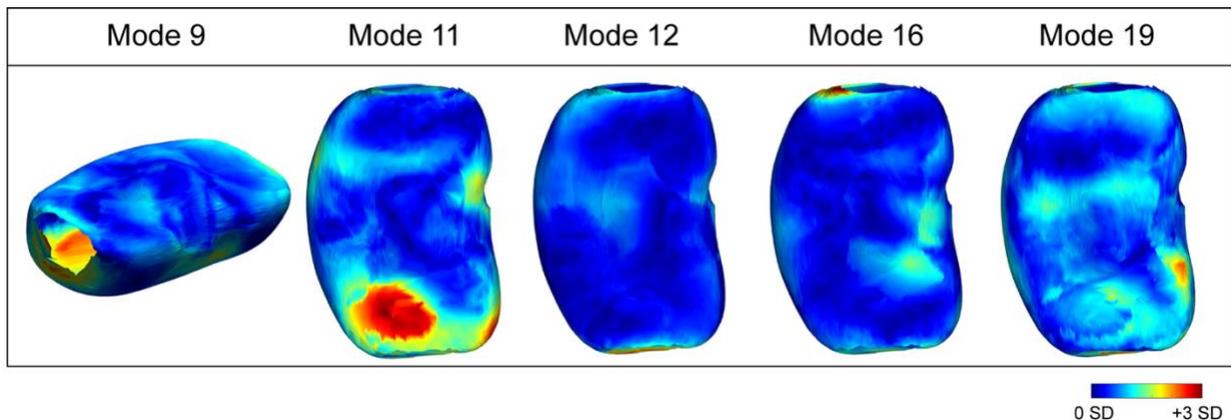


Fig 1: The significant principal component analysis (PCA) modes of the proximal tibia. Each mode depicts vertex displacement of  $\pm 3$  SD from the mean shape. Each three-dimensional model was positioned to highlight the prominent feature of the respective mode.