Three-Dimensional Statistical Shape Modeling of the Femur to Identify Morphological Risk Factors for Anterior Cruciate Ligament Injury: A Comparative Study Between Injured and Uninjured Subjects

SOHEUN LEE, Min Jung, Kwangho Chung, Hyunsoo Moon, Se-Han Jung, Sung-Hwan Kim

INTRODUCTION:

Anterior cruciate ligament (ACL) injuries accounts for approximately 50% of all knee injuries, frequently occurring in young, active individuals and increasing the risk of osteoarthritis. Traditional 2D radiographic studies have limitations in accurately visualizing anatomical structures, leading to inconsistent findings. Recent developments using automated landmark detection and 3D statistical shape modeling (SSM) have allowed for objective and efficient analyses. This study aimed to utilize SSM to identify morphological differences between ACL-injuries and controls and to evaluate a machine learning model to predict ACL injuries

METHODS:

The study included 120 subjects, consisting of 60 ACL-injuries and 60 controls. Propensity matching was performed to adjust for gender, age, height, weight, and laterality. All CT scans were acquired using a Siemens Somatom Sensation 64 scanner and processed into 3D surface models (STL files) using Mimics and 3-Matics software. Automated landmark registration was performed using ALPACA within the 3D Slicer platform, followed by Generalized Procrustes Analysis (GPA) and Principal Component Analysis (PCA) to create the SSM model. Logistic regression and multivariate analysis (MANOVA) were conducted to identify principal shape variations associated with ACL injuries. Machine learning classifiers including LDA, SVM (linear and RBF kernels), K-NN, and Random Forest were evaluated using 5-fold cross-validation.

RESULTS:

Morphological comparison revealed that ACL-injuries exhibited characteristic narrowing of the intercondylar notch, anteriorization of the trochlea, and asymmetrical displacement of the femoral condyles.

Principal component analysis identified PCs 1, 2, 4, 6, 7, 8, and 9 as significantly associated with ACL injuries ($p < 0.05$). Key shape deformations included notch constriction (PC1), epicondylar elevation (PC2), and increased condylar asymmetry (PC6, PC7, PC9). Shape trends were visualized using ±3SD models and sigmoid analysis.

Among five classification models, Random Forest and Linear Discriminant Analysis achieved the highest predictive performance (AUC = 0.851). Random Forest showed superior sensitivity, while LDA, SVM (linear), and k-NN demonstrated well-balanced specificity and sensitivity, indicating their potential utility in clinical ACL injuries screening based on morphological features.

DISCUSSION AND CONCLUSION:

ACL injuries were associated with distinct femoral morphological patterns, including condylar asymmetry, shaft anteriorization/lateralization, and intercondylar notch narrowing, regardless of sex.

In males, trochlear anteriorization and supracondylar elevation suggest internal rotational misalignment. While in females, lateral condyle narrowing with localized epicondylar widening and shaft anteriorization indicate external rotation and altered patellofemoral mechanics. These features may contribute to increased ligament strain and higher risk of ACL injuries.