Computational Knee Models Reveal Greater Estimated Anterior Cruciate Ligament (ACL) Forces During Simulated Pivot Shift in Female Athletes with Noncontact ACL Injuries: Case-Control Analysis

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INTRODUCTION:

Noncontact anterior cruciate ligament (ACL) injuries remain a significant problem in young, female athletes who participate in sports involving frequent pivoting. Current risk assessment tools, such as 3D motion analysis of a drop-jump landing, have demonstrated inconsistent ability to identify those who will suffer a noncontact ACL injury. Because combinations of unique geometric features of tibiofemoral anatomy (e.g., lateral tibial slope, femoral notch width) are related to risk of ACL injury, physics-based computational models, which simulate the complex interactions of knee geometries, may improve the ability to identify those at heightened risk of noncontact ACL injury. Thus, using previously collected knee MRI data from a case-control study of ACL-injured female athletes matched to uninjured teammates, this study had three objectives: 1) to create athlete-specific, 3D, physics-based computational knee models; 2) to estimate ACL forces during a simulated pivot shift loading sequence using these computational models; and 3) to characterize the relationship between estimated ACL force and risk of first-time, noncontact ACL injury.

METHODS: Previously collected MRI data from 60 female athletes suffering first-time, noncontact ACL rupture and 60 sex-, age-, and sport-matched controls from the same team were utilized. Imaging was obtained on contralateral, uninjured knees of injured athletes, and the same side of matched controls. To accomplish our first objective, volumetric representations of tibiofemoral bone, articular cartilage, and menisci were segmented and incorporated into a physics-based computational modeling pipeline (**Figure 1**). Next, we applied a sequence consisting of 100 N of compression, an 8 Nm valgus moment, and a 30 N anterior-directed load to simulate a pivot shift maneuver. At the peak applied load, we recorded the model-based estimate of ACL force. These ACL forces were compared between cases and controls using a paired Student's *t*-test ($\alpha = 0.05$). The discriminative ability of ACL force to identify injured versus uninjured athletes was assessed using the area under the receiver-operating characteristic curve (AUROC). Logistic regression was used to quantify the risk associated with increased ACL force, expressed as an odds ratio ($\alpha = 0.05$).

RESULTS:

Estimated ACL forces were, on average, 22.5 N (95% CI: 6.7 – 38.3 N) greater in injured athletes than in their uninjured teammates (mean ± SD: 119.0 ± 41.0 N vs. 96.5 ± 42.7 N; p=0.003; **Figures 2** and **3**). Of the 60 injured athletes, 70% (n=42) had greater estimated ACL forces than their uninjured teammates. Using ACL force to classify athletes as either injured or uninjured had an AUROC of 0.65 (0.56 – 0.74). Using 115.4 N as a threshold to classify athletes as either high-risk or low-risk, sensitivity was 0.67 and specificity was 0.63. The odds ratio for each one-SD increase in ACL force was 1.73 (1.18 – 2.55; p=0.005), indicating a 73% increase in likelihood of ACL injury for each one-SD increase in force.

DISCUSSION AND CONCLUSION:

This physics-based computational model revealed a significant association between increased ACL force and risk of ACL injury in female athletes. Notably, the model estimated greater ACL forces in injured athletes compared to uninjured controls. The use of athlete-specific 3D knee models within our computational framework allows for a detailed investigation of the relationship between knee biomechanics and ACL injury risk. Furthermore, the discriminative performance of the model (AUROC > 0.5) suggests potential utility as an adjunct screening tool for ACL injury risk in female athletes. However, given the moderate sensitivity and specificity obtained, further refinement of this model is likely necessary to improve performance. For instance, it may be valuable to incorporate additional risk factors (e.g., knee laxity, BMI) or to simulate loading sequences aside from a pivot shift. The association between heightened ACL force and injury risk highlights the importance of addressing unfavorable knee mechanics to enhance injury risk assessment and prevention strategies for female athletes.

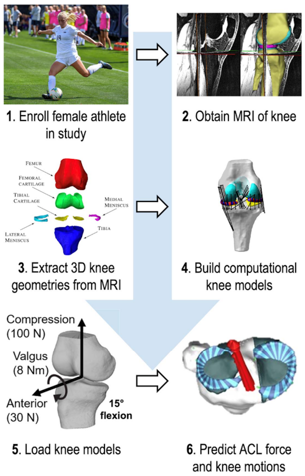

Figure 1. Overview of computational modeling workflow for prediction of ACL force and knee motions during a simulated pivot shift maneuver.

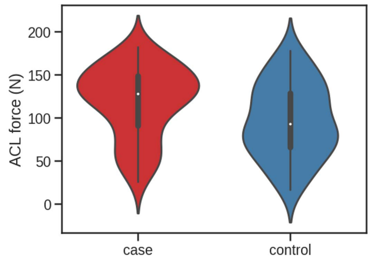

Figure 2. Violin plots showing the distribution of ACL force in cases and controls.

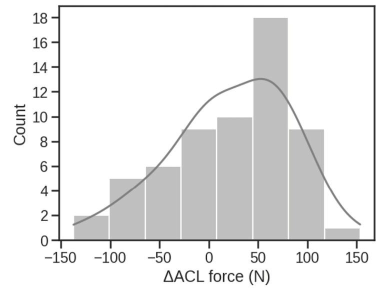

Figure 3. Histogram showing the distribution of the difference between ACL force in ACL-injured cases and matched controls during a simulated pivot shift. Positive numbers indicate greater ACL force in ACL-injured cases.