

# Females Exhibit Excess Coupled Internal Tibial Rotation Driving High ACL Forces in Response to an Applied Valgus Moment Compared to Males: A Sex-Specific Computational Modeling Study in 168 Young High-Risk Athletes

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**INTRODUCTION:** Young, female athletes who participate in cutting and pivoting sports are disparately vulnerable to noncontact anterior cruciate ligament (ACL) ruptures relative to males [1]. Previous research has implicated sex-differences in tibiofemoral bone and cartilage geometry as a potential explanation for this disparate risk. Recent work from our laboratory expanded on this hypothesis by creating computational knee models of 120 female and 48 male, injured and uninjured high-risk athletes. These models were designed to estimate ACL force as a function of individuals' tibiofemoral geometry under loads simulating a clinical pivot shift exam (combined axial compression, valgus moment, and anterior tibial force). This experiment revealed higher ACL force at the peak applied pivot shift loads in females compared to males [2]. While this highlighted an important mechanical difference in female knees, it remains unclear which component of these applied loads led to the disparate elevations in ACL force in females relative to males, and how this occurred kinematically. We therefore asked (1) which subcomponent of the loads simulating the clinical pivot shift exam is responsible for the disproportionate rise in ACL force observed in female knees and (2) which component of the resulting tibiofemoral kinematics is most strongly related to this rise in ACL force?

**METHODS:** With IRB approval we used magnetic resonance imaging (MRI) data from 168 high school and college athletes (120 females, 48 males), consisting of cases with first-time noncontact ACL injury and uninjured controls matched 1:1 by sex, age, and sports team. A published subject-specific computational modeling method was applied to MRI data from the uninjured knee of cases and matched knees of controls [3]. We created 3D renderings of the tibiofemoral bone, articular cartilage, and meniscal geometries, then identified ligament attachments. Tissue stiffnesses and ligament slack lengths were standardized based on published population means and algorithms. For each knee model, axial compression (100 N), a valgus moment (8 Nm), and an anterior force (30 N) were applied in series to the tibia (femur fixed at 15° flexion). These loads increase ACL force and are key components of knee loading during the clinical pivot shift exam and cutting-pivoting sports maneuvers. The model outputs were the change in ACL force and tibiofemoral kinematics, including ITR, valgus angulation, and anterior tibial translation (ATT) in response to each sequential step of the simulated pivot shift (1, axial compression; 2, a valgus moment added to axial compression; 3, an anterior tibial force added to axial compression and the valgus moment). Differences in the increase in ACL force in response to each subcomponent of the pivoting load between all males and all females were analyzed with unpaired t-tests ( $\alpha = 0.05$ ). Once this key subcomponent(s) was identified, simple and multiple linear regressions were used to characterize the relationship between changes in ACL force and changes in ITR, valgus angulation, and ATT. Model outputs included regression coefficients ( $\beta$ ), and p-values, and R<sup>2</sup> values.

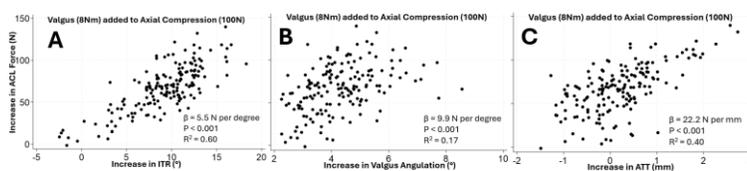
**RESULTS:** The mean increase in ACL force under to axial compression in all subjects was 16.2 ± 8.9 N, which was similar in males (14.2 ± 9.3 N) and females (17.1 ± 8.6 N) ( $p = 0.06$ ). The mean increase in ACL force with a valgus moment added to axial compression in all subjects was 66.9 ± 27.7 N, and this increase was greater in females (70.9 ± 28.0 N) compared to males (56.6 ± 24.1 N) ( $p = 0.002$ ). The mean increase in ACL force with an anterior tibial force added to axial compression and the valgus moment was 34.8 ± 7.7 N, which was similar in males (34.2 ± 8.0 N) and females (35.1 ± 7.6 N) ( $p = 0.49$ ). The loading step that differentiated the sexes was adding a valgus moment following axial compression. Using simple linear regressions, increases in ACL force with a valgus moment added to axial compression were most strongly related to increases in ITR ( $\beta = 5.5$  N per degree,  $p < 0.001$ ,  $R^2 = 0.60$ ), followed by ATT ( $\beta = 22.2$  N per mm,  $p < 0.001$ ,  $R^2 = 0.40$ ), and valgus angulation ( $\beta = 9.9$  N per degree,  $p < 0.001$ ,  $R^2 = 0.17$ ) (Figure 1). The strength of the relationship between each kinematic variable and ACL force was not altered when using a multiple linear regression including all three kinematic variables.

**DISCUSSION:** These data suggest that application of a valgus moment to an already axially compressed knee may drive high ACL forces, not because the resulting valgus angulation itself drives high ACL forces, but because such valgus moments may cause coupled ITR and increased ACL force, especially in females. This was supported by the finding that the subcomponent of the pivot shift loading sequence that was responsible for the increased ACL force observed in females relative to males was the application of a valgus moment following axial compression. Furthermore, the increase in ACL force that was observed in this key aspect of the loading sequence was most strongly associated with increases in ITR. Our computational model controls for ligament and soft tissue mechanical properties, thus model outputs for each knee are a function of that subjects' unique tibiofemoral bone and cartilage geometries. Thus, collectively, our results suggest that female knee geometry may contribute to a sex-specific mechanical sensitivity to applied valgus moments to the knee, a sensitivity which is chiefly characterized by a propensity to exhibit coupled ITR that increases ACL force. These results are in line with current clinical thought emphasizing the importance of rotational mechanisms of ACL failure and suggest that injury prevention and rehabilitation programs may benefit from emphasizing movement patterns that reduce valgus moments to the knee during axial weight bearing activities. Furthermore, surgical interventions that augment ACL reconstructions to reduce ACL loading may benefit from considering how to decrease coupled ITR to offload the ACL.

**SIGNIFICANCE:** These data suggest that in high-school and college, high-risk, cutting-and-pivoting sport athletes, an applied valgus moment following axial compression leads to coupled ITR that drives high ACL forces. Additionally, female knees in this population may be particularly sensitive to valgus loading that causes this coupled ITR and increased ACL force relative to males due to their tibiofemoral bony and articular cartilage geometries.

**REFERENCES:** [1] Beynnon 2014 AJSM. [2] Wheatley 2024 ORS Annual Meeting. [3] Kia 2016 J Biomech Eng.

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**Figure 1:** Simple linear regressions examining the relationships between changes in ACL force (dependent variable) and changes in knee kinematics (independent variables) (A, ITR; B, valgus angulation; C, ATT) as a function of the adding of a valgus moment to the previously applied axial compression.