A Geometry-Specific Computational Model Can Distinguish Knees Prone to Increased ACL Force in Response to Valgus Loading

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Summary
Computational models that incorporate subject-specific tibiofemoral geometries may be useful tools to estimate knee mechanics despite lacking subject-specific soft tissue properties. To establish credibility, they require corroboration with physical experiments. To that end, ten cadaveric knees were tested under valgus loads which are thought to contribute to non-contact ACL injury. ACL force and kinematics were measured and compared on a one-to-one basis to corresponding computational models. ACL force and internal tibial rotation were correlated between the two methods ($p \leq 0.02$) while anterior tibial translation was not. Therefore, geometry-specific computational models may identify those prone to increased ACL force with valgus loading, even when ligament properties in the model are standardized.

Introduction
Young athletes participating in cutting and pivoting sports are vulnerable to sustaining noncontact anterior cruciate ligament (ACL) rupture [1]. Articular surface geometries are risk factors for ACL injury and drive knee mechanics [2]. Thus, measuring knee mechanics, like ACL force, under loads associated with noncontact ACL injury is critical to identify those at the greatest risk of injury. Computational models incorporating subject-specific knee geometries can estimate ACL force non-invasively and under loads that are potentially injurious. However, such models require corroboration with corresponding physical experiments to establish their credibility. Thus, we used an experimental-computational knee modeling workflow [3] to estimate knee mechanics and compare outputs to a corresponding cadaveric experiment. We hypothesized that *in silico* estimates of ACL force and tibiofemoral kinematics are correlated with corresponding *in vitro* measurements.

Methods
Cadaveric Experiment: Ten unpaired cadaveric knees (5 females; age: 33 ± 7 years) were procured. Anatomical coordinate systems were defined from bony landmarks. Knees were mounted to a robotic manipulator and tested using established protocols [3] (Fig. 1). Compression (100 N) and a valgus moment (8 Nm) were applied serially at 15° of flexion. All degrees of freedom except flexion were left unconstrained. Outcomes were: 1) ACL force at peak applied load, 2) internal tibial rotation (ITR), and 3) anterior tibial translation (ATT).

Computational Model: A previously published modeling pipeline was utilized. Briefly, tibiofemoral bone, cartilage and meniscal geometries were segmented from magnetic resonance imaging. Subject-specific ligament insertions and origins were identified [3]. Soft tissues were given population-mean structural properties, and slack lengths were standardized [3]. The same coordinate systems were registered between computational and cadaveric experiments. The same loads were applied, and the same outcomes were collected as for the cadaveric experiment. The correlation between model and experiment outcomes was assessed via Pearson correlation coefficient (α=0.05) and regression coefficients were reported.

Results and Discussion
The correlations between *in silico* estimates and experimental measurements were r = 0.81 (p = 0.005) for ACL force (Fig. 2A), r = 0.73 (p = 0.02) for ITR (Fig. 2B), and r = -0.27 (p = 0.45) for ATT (Fig. 2C). Regression coefficients for ACLF and ITR were 0.64 N/N and 0.49 °/°, respectively.

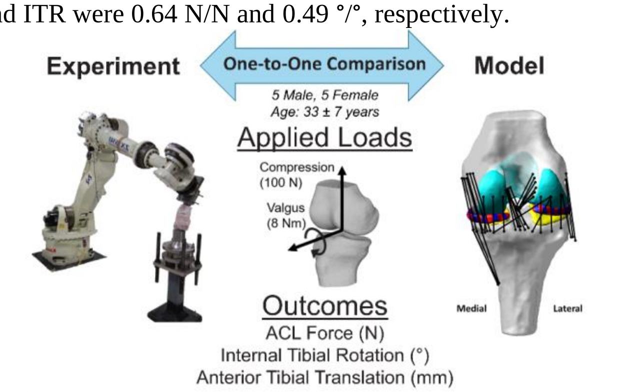

Figure 1: Knee mechanics were compared between cadaveric experiment and geometry-specific computational model

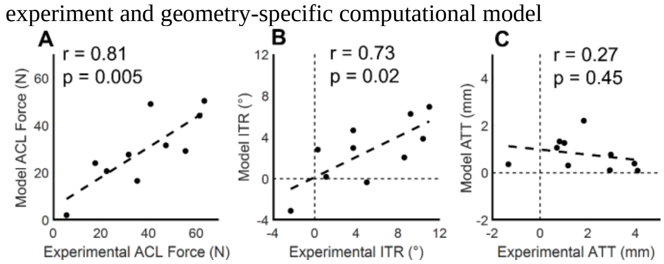

Figure 2: Model estimates plotted against experimental outcomes for (A) ACL force, (B) internal tibial rotation (ITR), and (C) anterior tibial translation (ATT)

Conclusions
The strong correlation for ACL force (r = 0.81) indicates that this geometry-specific *in silico* model may distinguish those knees prone to increased ACL force in response to valgus loading. Regression coefficients <1 indicate that models with population-mean ligament properties may systematically underestimate ITR and ACL force. Tuning parameters like ligament stiffness and slack length may improve agreement. However, a geometry-specific model may be clinically informative in situations where only subject-specific geometric data are available.

Acknowledgments
Clark and Kirby Foundations, R21AR073388

References
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