Can Knee Bracing Prevent Ligamentous Injury? Computational Models Could Be the Key

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INTRODUCTION: Injuries to the medial collateral ligament (MCL) and anterior cruciate ligament (ACL) are prevalent, where MCL injury rates in the National Football League were 0.155 injuries per team-game and an additional 400,000 ACL injuries occur annually [1-3]. Knee bracing is commonly believed to prevent or lessen ligamentous injury in the athletic setting; however, their usefulness remains controversial [4]. The ability to predict injury to the MCL and ACL using computational modeling both with and without knee bracing may provide support for the proactive usage of knee bracing. Thus, the long-term goal of the work is to develop a methodology for 3D finite element modeling of the tibiofemoral joint with applications to ligamentous injury and the effects of knee bracing. However, the first step is to develop and validate subject specific models with experimental data to ensure the model appropriately predicts joint function. The objectives of the current work were: 1) to develop an approach for finite element modeling of the tibiofemoral joint, 2) to determine optimal mesh density for the MCL, 3) to assess the model's sensitivity to MCL mechanical properties, and 4) to validate the kinematic behavior of the model.

METHODS: One fresh-frozen cadaveric knee (37 years, male) was thawed for 24 hours and underwent magnetic resonance imaging. The 3D subject specific geometries of the femur, tibia, MCL, ACL, menisci, and tibial plateau cartilage were then reconstructed from the images, and a finite element model of the knee was constructed using FEBioStudio (v2.10.0)[5]. The tibia and femur were modeled as rigid bodies and soft tissues were initially meshed using TetGen (Tet10 elements). The nodes of the proximal and distal MCL and ACL insertions were rigidly fixed to femur and tibia, respectively, and the meniscal roots were rigidly fixed to the tibia. The MCL, ACL, and menisci were represented as transversely isotropic hyperelastic and cartilage was represented as linear elastic with average parameters from the literature [6-10]. In full-extension and 30° of flexion, a 1) 10Nm valgus torque, 2) 134N anterior load, or 3) 10Nm internal torque was applied to the tibia simulating the experimental loading conditions applied using a robotic testing system (MJT model FRS2010). As a starting point, mesh convergence was performed for the MCL. Mechanical properties for the MCL were tuned using the valgus rotation in response to a valgus torque in full-extension. To determine the appropriate mesh density to predict values of valgus rotation that did not change by >5% with additional refinement, two additional models with mesh densities of twice and half the number of elements as the original mesh were analyzed and simulation time was recorded. Sensitivity analyses were performed to determine the sensitivity of predicted valgus rotation at full-extension to mechanical properties of the MCL (modulus and λmax (collagen fiber stretch for straightened fibers)). Twenty-five simulations were run (design of experiments approach) with varying values of the modulus and λmax based on the means and standard deviations in the literature [11]. The mechanical properties of the MCL were tuned based on the modulus and λmax that minimized the difference between the experimental and simulated valgus rotation in full-extension. Outcome parameters included the simulated amount of valgus rotation (30° of flexion) in response to a 10Nm valgus torque, anterior translation (full-extension and 30° of flexion) in response to a 134N anterior load, and internal rotation (full-extension and 30° of flexion) in response to a 10Nm internal torque. For the respective loading condition, the model was considered validated if valgus rotation, anterior translation, and internal rotation were within 2.5°, 4.4mm, and 6.3° of the experimental values, respectively. Validation criteria were based on the root-mean squared error between experimental and simulated kinematics of established models (mean ± 2SD)[12].

RESULTS: Changes in mesh density had a minimal effect on valgus rotation, where the mesh with half the number of elements experienced 6.5% less valgus rotation (simulation time reduced 12.2%) and the mesh with twice the number of elements experienced a 1.2% increase in valgus rotation (simulation time increased 37.4%) compared to the baseline mesh. The model's valgus rotation was highly sensitive to λmax between the ranges of 1.008 to 1.046 but was insensitive to λmax with values ≥1.046 (Figure 1). Utilizing the average λmax from the literature, the model's valgus rotation was insensitive to the modulus. Utilizing the tuned MCL mechanical properties, the largest differences between experimental and simulated kinematics for translations and rotations were 4.1mm for anterior translation in response to an anterior load and 0.9° for internal rotation in response to an internal torque at 30° of flexion (Table 1).

DISCUSSION: A subject specific computational model of the tibiofemoral joint with tuned MCL mechanical properties was successfully constructed and validated against experimental kinematics. Based on the mesh convergence analysis, it was concluded that the original mesh provided a balance between accuracy and computational expense and was utilized for sensitivity analysis. The model demonstrated good agreement with valgus rotation in response to a valgus torque at 30° of flexion, demonstrating the tuning process's ability to predict function of the MCL. However, larger differences for anterior translation in response to an anterior load were found between experimental and simulated kinematics. Thus, mesh convergence and tuning of the ACL mechanical properties in response to an anterior load at full-extension may be needed to better represent subject specific ACL function. Overall, the simulated kinematics were still within errors reported from established modeling workflows providing support that the model reasonably predicts subject specific kinematics. Future work includes the construction and validation of additional subject specific models, and the novel combined incorporation of knee bracing and continuum damage mechanics to predict MCL and ACL injury in response to traumatic loads. The results will then be validated against data in the literature for MCL and ACL strains in response to traumatic loads. To ensure accuracy of the results, additional mesh convergence analyses may be required to determine the effect of mesh density on strain patterns in the MCL and ACL.

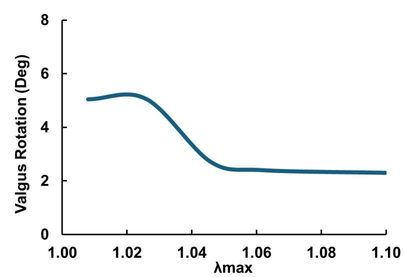

Figure 1: Sensitivity of model's valgus rotation to changes in collagen fiber stretch for straightened fibers.

SIGNIFICANCE/CLINICAL RELEVANCE: A computational framework for the tibiofemoral joint capable of incorporating damage mechanics and knee bracing was developed for future investigation of ligamentous injury.

Table 1: Comparisons between experimental and simulated kinematics for each joint position in response to a valgus torque, anterior load, and internal torque.

Flexion Angle	Outcome Parameter	Experimental	Simulation
Full-Extension	Internal Rotation (°)	16.3	15.8
	Anterior Translation (mm)	2.8	2.2
30° Flexion	Valgus Rotation (°)	1.6	2.2
	Internal Rotation (°)	29	28.1
	Anterior Translation (mm)	6.4	2.3

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