OPEN KNEE: CAPACITY TO REPRODUCE ANTERIOR CRUCIATE LIGAMENT DEFORMATIONS

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1. ABSTRACT

Simulation-based explorations of the knee have commonly relied on finite element analysis. For example, for the anterior cruciate ligament, studies explored injury mechanisms, impingement, and load transmission. Finite element analysis of the knee requires a model representative of joint and tissue level mechanics. In this study, our goal was to establish the predictive capacity of Open Knee, an openly developed and disseminated tibiofemoral joint model, for specimen-specific representation of anterior cruciate ligament deformation. Specimen-specific mechanical testing data, representative of a 100 N anterior drawer test at 0° and 30° flexion angles, were utilized. The data set included ligament length change acquired with a DVRT (MicroStrain, Inc., Williston, VT) placed on the anteromedial bundle. The loading and boundary conditions of the experiment were reproduced in simulations. The association of model predicted ligament length changes against those measured by the DVRT was established by linear regression. While predicted and measured ligament deformations were highly correlated, simulations consistently overestimated relative change in anterior cruciate ligament length. Overpredictions were more pronounced for initial and high loading levels but less for the middle range. It is possible that current representation of the anterior cruciate ligament and also that of other anatomical structures, e.g. menisci, particularly related to assignment of generic material properties, may describe such discrepancies. Future work, to test such statements is planned, and can also be accomplished by others, given the open nature of development and dissemination of the knee model.

2. INTRODUCTION

Simulation-based exploration of knee biomechanics has commonly relied on finite element analysis. For the anterior cruciate ligament (ACL), many modeling studies have been conducted to explore injury mechanisms [1], impingement [2], and load transmission [3]. Like any other modeling studies, finite element analysis of the knee and its components requires a robust model representative of joint and tissue level mechanics [4]. Recently, we have openly developed and disseminated a finite element representation of the tibiofemoral joint, Open Knee (https://simtk.org/home/openknee) [5], and explored its capacity to reproduce normative passive joint kinematics [6]. In

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this study, our goal is to establish the predictive capacity of Open Knee for specimen-specific representation of gross ACL deformation during an anterior drawer test. A successful evaluation process will increase confidence in finite element analysis of the knee underline in situ behavior of the ACL. It will also establish a computational tool for virtual prototyping of interventions to reproduce this ligament's biomechanical function. Even when unsuccessful, a detailed depiction of model's failure to reproduce experimental results will potentially identify directions for model improvement.

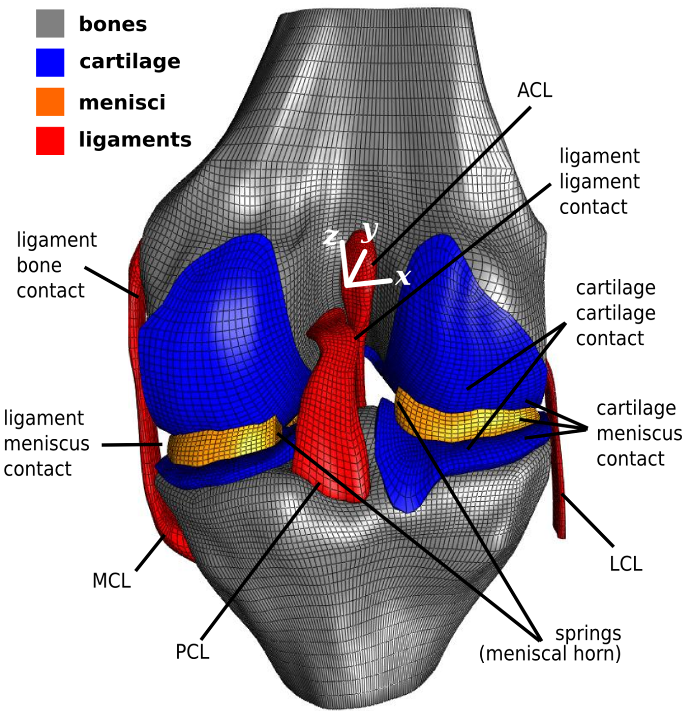

Figure 1. Components of Open Knee, a finite element representation of the tibiofemoral joint, as shown from a posterior view, from Open Knee User's Guide [5]. In this study, contact between collateral ligaments and bone/menisci were not modeled. The experimental scenario for anterior drawer test was replicated by the application of a posterior force on the femur at the origin of the femoral coordinate system. Flexion was prescribed; the rest of femoral rigid body degrees of freedom were set free; tibia was fixed.

3. METHODS

Open Knee, a finite element representation of the tibiofemoral joint, was reconstructed from a right cadaver knee (70 year old female, 77.2 kg) [5] (Figure 1). For the same knee, mechanical testing data representative of anterior drawer were also available [7]. For this study, anterior laxity data acquired at 0° and 30° flexion (all other tibiofemoral joint degrees of freedom free), for a 100 N tibial load (with 10 N increments) were utilized. The data set included gross measurements of ACL length change, acquired with a DVRT (MicroStrain, Inc., Williston, VT). The DVRT was placed on the anteromedial bundle of the ACL, with the distal end approximately 3 mm above the tibial insertion and the proximal end approximately 11 mm proximal to distal end of the DVRT [7]. Time history of the loading and boundary conditions of the experiment were reproduced in the finite element analysis, utilizing approximately the same joint coordinate system [8]. FEBio (http://www.febio.org), a nonlinear finite element analysis software package for biomechanics, was used for implicit dynamic simulations. Predicted ACL deformations were calculated from the distance between nodes representative of DVRT insertion points on the model (Figure 2). For both the model and experiment, and at both flexion angles, the relationship between anterior drawer force and ACL length change was established. The association of model predicted change in ACL length against those measured by DVRT was conducted by scatter plot regression, separately for 0° and 30° flexion [4]. Kinematics of the tibiofemoral joint were also quantified as a function of anterior drawer force, utilizing the Grood and Suntay convention [8].

4. RESULTS & DISCUSSION

As expected, the application of an anterior drawer force resulted in changes in ACL length regardless of flexion angles (Figure 3, left). Model predicted ACL deformation exhibited a nonlinear toe region followed by a linear region as a function of the anterior force. In the experiments, on the other hand, this nonlinear behavior was more pronounced with the ACL length change reaching an asymptote at high anterior forces. While experimental and measured changes in ACL length were highly correlated, simulations consistently overpredicted gross ACL deformation (Figure 3, right). This was more pronounced for initial and high loading levels but less for the middle range. Slopes of linear fit, which established the relationship between experimental and model predicted ACL length change, were 1.50 and 2.52 for 0° and 30° flexion, respectively.

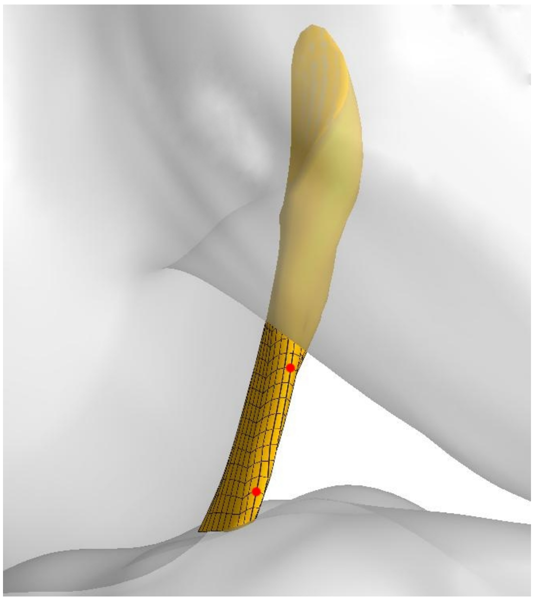

Figure 2. Model predicted length change of the anterior cruciate ligament was calculated from the distance between model predicted locations of two nodes (indicated in red). These nodes approximated the insertion areas of the DVRT, which was utilized in the experimentation to calculate anterior cruciate ligament length change [7]. The ligament is shown from an anterior-medial direction.

It is possible that representation of the ACL properties, i.e. constitutive parameters, lack of in situ strain [9], may contribute to the discrepancies in its predicted and measured deformations. Nonetheless, predicted tibiofemoral kinematics also exhibited large discrepancies (Figure 4), indicating that other components of the joint, i.e. collateral ligaments, and menisci, may need attention. If not represented appropriately, these structures may not restrain movement under loads and result in erroneous positioning of ACL insertion and origin, which in turn influences the deformation predicted within. For example, simulation of the anterior loads resulted in an internal rotation of tibia, which was an unexpected behavior when compared to experimental rotations. In addition, when the joint moved from 0° flexion to 30° flexion, simulation results largely deviated from measurements of tibiofemoral joint kinematics. This most likely caused the unexpected behavior of the ACL in flexion, during which the mismatching kinematics may have stretched the ACL and caused an “inverted” behavior of ligament length change when compared to experiments (Figure 3).

At this stage, Open Knee, at least for a loading condition representative of an anterior drawer test, does not reliably predict specimen-specific ligament deformations and kinematics. Nonetheless, a complete one-to-one comparison of model results against experimentation allows an in-depth understanding of problem areas for a given model. While both the model and experimental anterior translations increased with anterior loading, the model appeared to be stiffer in that direction as indicated by the predicted

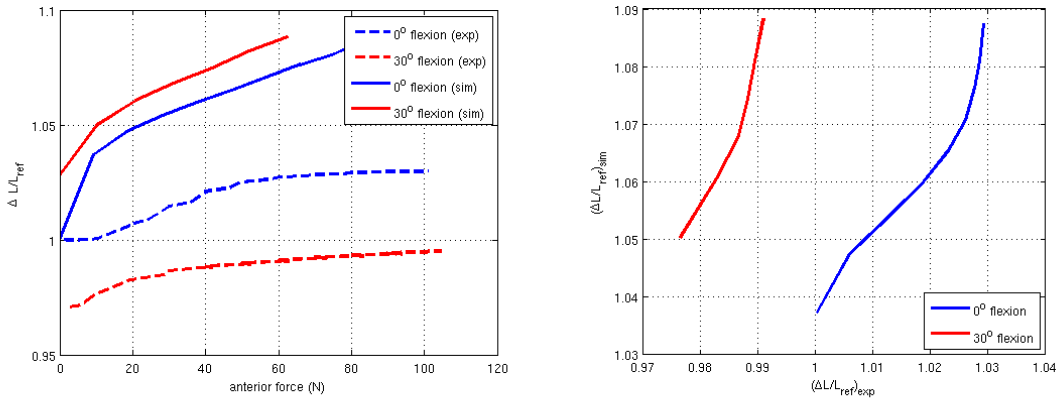

Figure 3. Relative length change in the anterior cruciate ligament ($\Delta L/L_{\mathrm{ref}}$) as predicted by the model (see Figure 2) and as measured during experimentation [7], left. Both the model and the experiment exhibited a nonlinear-toe region. The reference length, L_{ref}, was obtained at unloaded 0° flexion for all cases. On the right, one can observe the relationship between experimental measurements and model predictions. Overall, simulations overpredicted the anterior cruciate ligament length change. During the experiments, anterior cruciate ligament get shorter with 30° flexion, yet the simulations predicted that it would stretch.

anterior kinematics of the joint having a smaller range of movement. Simply evaluating anterior translation predictions alone, one may expect the predicted ACL length change to be low. Nonetheless, this is not the case. A full depiction of all degrees of freedom of the joint allowed identification of off-axis movements (Figure 4) that potentially caused undesirable model predictions. Large internal rotation of the tibia, combined with mismatching medial positioning, may have caused large deformations of the ACL when compared to the experiments. It is also worth noting other assumptions that may have caused mismatching model predictions. Alignment of the model and experiment coordinate systems relied on anatomical landmarks, which may have caused erroneous positioning of the joint origin where the anterior load was applied.

Recent developments in uncertainty estimation for finite element analysis of the knee [10] provide pathways to explore sensitivity of our model predictions to be conducted in a systematic manner. Given the open nature of the model presented in here, this laborious work can be conducted in a collaborative fashion, not only by the research team but also by anyone who is interested in utilization of knee models for research and clinical purposes. In following, reliable estimation of joint mechanics, and ligament deformations, e.g. Figure 5, can be obtained to guide research studies and medical interventions.

5. ACKNOWLEDGMENTS

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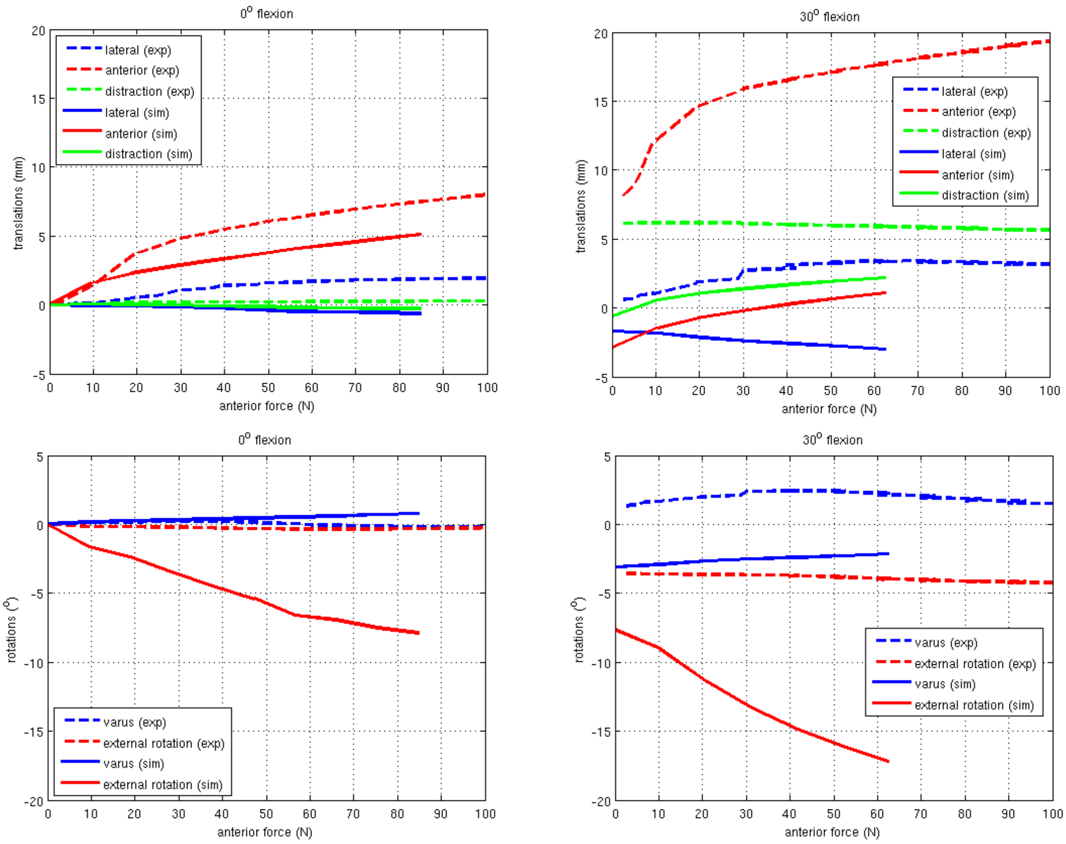

Figure 4. Kinematics, as predicted by the model and also measured through robotics testing [7], during anterior drawer tests conducted at 0° and 30° flexion. All kinematic variables were calculated using the Grood and Suntay convention [8] from the transformation matrices describing the movement of tibia relative to femur. In all cases, unloaded 0° flexion was selected as the reference state. As an anterior load was applied to the model, an internal rotation of tibia was observed. This was not the case during the experiments and will likely describe some of the discrepancies in ligament length changes. As the joint went from 0° flexion to 30° flexion, i.e. for the unloaded case, large deviations in kinematic response was observed between the model and the experiment. This may explain the discrepancies between predicted ligament length change and its experimental measurements, particularly at the flexed joint position (also see Figure 3). In all cases, anterior loading resulted in an increase in anterior translations.

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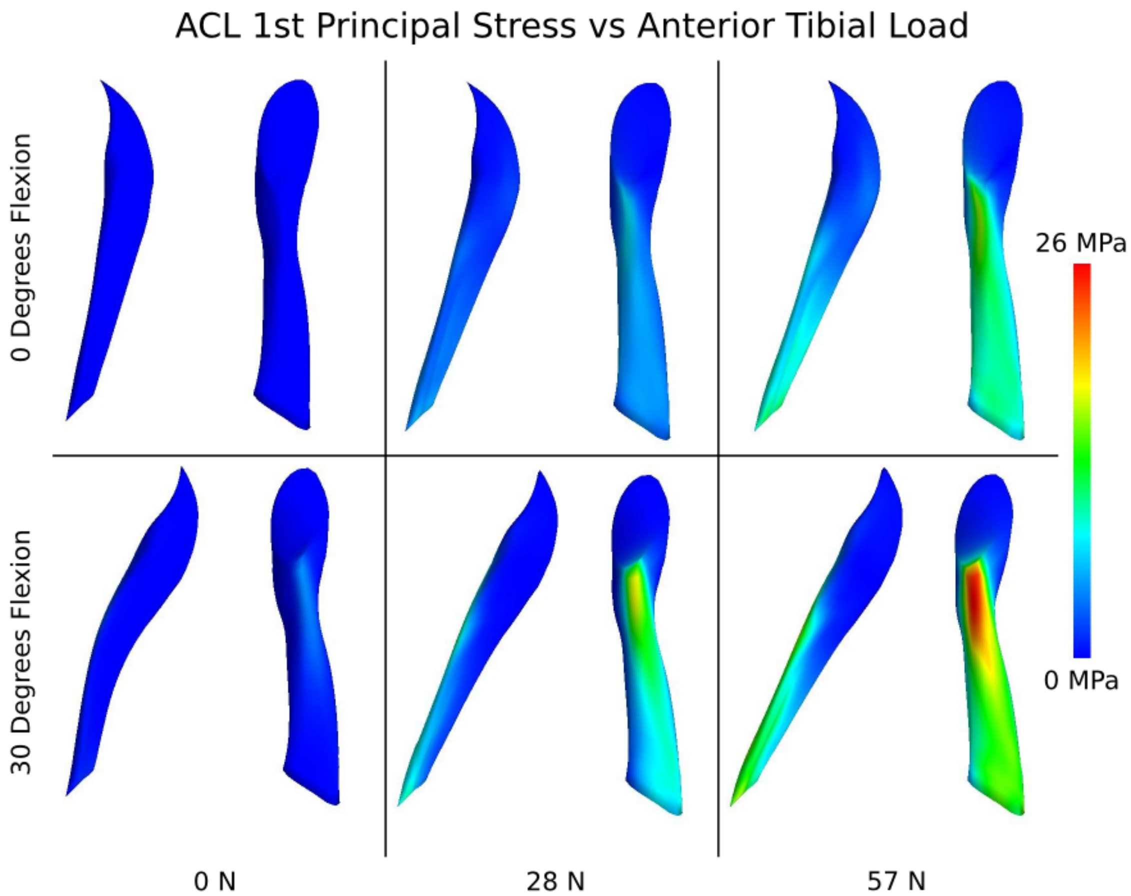

Figure 5. The 1st principal stress in the anterior cruciate ligament as a function of an anterior drawer force at 0° and 30° flexion. A sagittal view (from the medial side) is shown along with an anterior view of the ligament. The 1st principal stress was predominantly along the fiber direction, therefore it illustrates relative loading on individual regions of the ligament. Regardless of the flexion angle and the load, the anterior-superior region seemed to be loaded more than any other region. With flexion, bending of the anterior cruciate ligament was visible (row 2, column 1).