OPEN KNEE: A 3D FINITE ELEMENT REPRESENTATION OF THE KNEE JOINT

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INTRODUCTION

Finite element (FE) analysis has become an important tool in knee biomechanics to explore joint and tissue function, to understand injury mechanisms, study pathological joint mechanics and evaluate surgical performance. Numerous models have been developed and used (a recent PubMed search reveals 382 publications) and in many cases, multiple models were constructed independently to investigate similar questions [1,2]. If disseminated, computational tools and models can avoid the duplication of research effort and provide a means for investigators to reproduce the results from other laboratories [3].

The typical process for generating a validated, specimen-specific FE model involves: 1) imaging of a cadaver specimen, 2) gathering kinetic and kinematic data for the intact specimen, 3) material testing of the substructures, 4) reconstruction of anatomical geometry, 5) mesh generation, 6) constitutive modeling, 7) definition of boundary conditions, loads, and constraints, 8) mesh convergence analysis, and 9) validation and sensitivity analysis. The entire process can be a laborious task and often presents barriers for isolated research groups due to limited access to experimentation tools and/or engineering expertise. Subsequent scientific investigations with the validated model are usually a small fraction of the research time and resources. Our long-term research goal is to develop a knee joint model to describe and predict the passive kinematics of the knee, and provide an initial platform to investigate more detailed mechanics of joint substructures after modifications to address specific research questions. The objective of this presentation is to describe our initial efforts to develop a freely distributable model of passive knee mechanics, while providing the research community with all data that was used for model development as well as the model itself.

METHODS

Magnetic Resonance (MR) images of a right cadaver knee (70 y. o. female donor) were collected using a 1.0 Tesla extremity scanner (Orthone, ONI Medical Systems, Inc., Wilmington, MA) with the joint at full extension [4]. Robotic testing was performed using a hexapod (Rotopod R2000, Parallel Robotic Systems Corp., Hampton, NH) to collect passive load-displacement and torque-rotation data for the tibiofemoral joint in all six degrees of freedom [4].

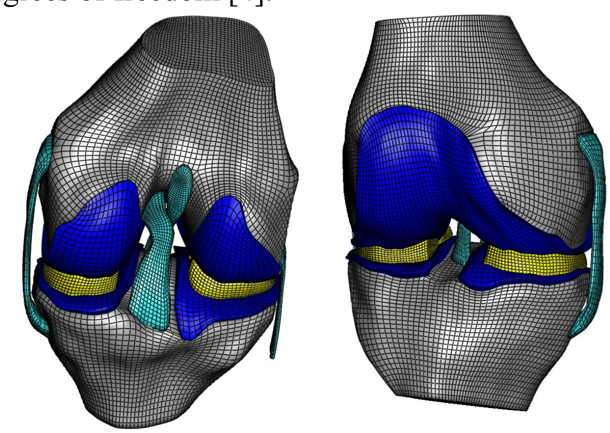

Figure 1: Hexahedral mesh of the tibiofemoral joint. Left-posterior view. Right - anterior view.

The geometries of the femur, tibia, anterior & posterior cruciate ligaments, medial and lateral collateral ligaments, articular cartilage, and menisci were extracted from MR images manually using VolSuite (http://www.osc.edu/archive/VolSuite). Spline curves represented the boundaries, and were used to generate parametric surfaces in Rhinoceros (McNeel, Seattle, WA). The surfaces were imported to TrueGrid (XYZ Scientific Applications, Livermore Inc., CA) and meshed with 133,295 hexahedral elements (Fig. 1). The mesh density may be adjusted later pending a mesh convergence study.

The femur and tibia were rigid. Cartilage and menisci were nearly-incompressible neo-Hookean materials [6]. Ligaments were nearly-incompressible, transversely isotropic, hyperelastic materials [6,7]. Ligament insertion areas were constrained to move with the rigid bone. Frictionless contact was defined between all structures that may come into contact. To test the solution process, a passive flexion was simulated by fixing the tibia and prescribing a 90° rotation of the femur about an approximate mediolateral axis, while leaving all other degrees of freedom free. For pre-processing, simulation, and post-processing, free and open-source software were employed: PreView, FEBio [5], and Postview, respectively (http://mrl.sci.utah.edu/software).

An open access philosophy was adapted for model construction to allow anyone to utilize and/or modify the model at all stages of development. The use of an open-source pre-processor and solver strengthens the capacity for others to use the model, and incorporate changes based on their scientific question. Documentation and dissemination for the experimentation and modeling are available at https://simtk.org/home/openknee, including a wiki, forums, and source code repository. This provides the scientific community a pathway to test, assess validity, provide recommendations, and implement new features.

RESULTS AND DISCUSSION

A preliminary tibiofemoral joint model was developed and is available at the site, including MR images, geometries, and mesh. Currently, the model is capable of simulating passive knee flexion from full extension to approximately 75 degrees of flexion (Fig. 2). It should be noted that, the purpose of this simulation was to test model robustness and no merit should be given to the output as additional simulations for validation are warranted.

FE representations of the knee will have limitations, depending on the scientific question. A rigorous verification and validation process needs to be employed. For example, if one is interested in ligament stresses, estimation of the in situ ligament strain at reference model configuration may become important [7]. Simplifications can be conducted on a need basis, i.e. if overall joint response is the variable of interest, the ligaments can be represented as line elements. The presented FE model of the knee joint is currently in a stage of infancy. Making it publicly available at this early stage is important for testing of the open-source development philosophy in the field of biomechanical modeling.

The research team not only seeks to provide a model which can be extended and modified to meet a particular researcher's need, but also to benefit from the expertise of numerous investigators who may use the model and provide feedback during its development. In return, model quality can be enhanced by wide-spread suggestion and criticism.

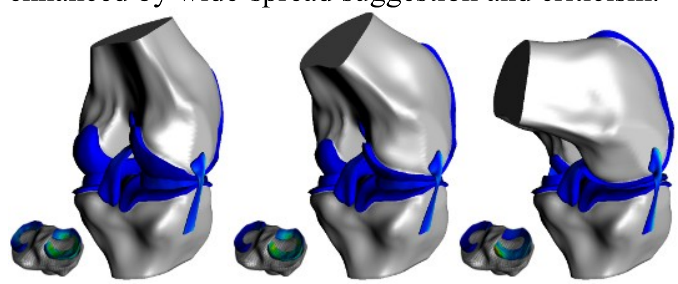

Figure 2: Simulation of knee flexion of approximately 75 degrees using FEBio. Von Mises stress distribution at 23°, 45°, and 75° flexion, from left to right.

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