Major Activities

The budget period of this progress report was 06/01/2016- 05/31/2019. In this final period of the project, major activities of Open Knee(s) primarily focused on model development for all eight specimens, specifically to bring them to a simulation-ready state. Activities for tissue mechanical characterization and data dissemination continued. Additional experiments were performed to acquire anatomical and mechanical data sets for additional virtual knees.

Specific Objectives

Overall goals of the project are (1) to provide an open, freely available, and collaborative development, testing, simulation and dissemination platform for *in silico* exploration of the biomechanics of healthy and diseased knees and (2) to develop *in silico* biomechanical models of healthy and diseased knee joints of different genders and ages, supported by specimen-specific joint and tissue level experimental mechanics.

Relevant to these goals, specific objectives planned for this budget period were development of full finite element models of all the specimens and continued experimentation. Additional activities were to engage with the Advisory Board and the community, and to disseminate information.

Significant Results

In the previous budget years, a total of 8 specimens were acquired, and magnetic resonance imaging and joint mechanical characterization data were collected. All the data were disseminated in its raw form on the project site. Specifications were developed and improved upon for image segmentation and geometry generation. Model development specifications were also developed along with in house Python scripts to automate the mesh generation and assembling a template full finite element model (Figure 1).

Our large set of preliminary testing on different tissue types (cartilage, meniscus, ligament) and a lack of complete testing related information in literature indicated concerns for reproducibility of tissue mechanical characterization. As a result, our testing focus pivoted to setting up a comprehensive tissue testing protocol with documented reproducibility. Tissue mechanical characterization protocols for cartilage were extensively worked on and finalized after rigorous testing. Specimen oks003 was chosen to be the first specimen for tissue characterization. Multiple cartilage samples were tested from the specimen under different testing conditions. To ensure that reliable data were obtained, every test was repeated three times and repeatability metrics were obtained (Figure 2). A total of 54 tests were conducted. Protocols are being optimized for meniscus, ligament and tendon material characterization and we anticipate tissue testing continue beyond project period.

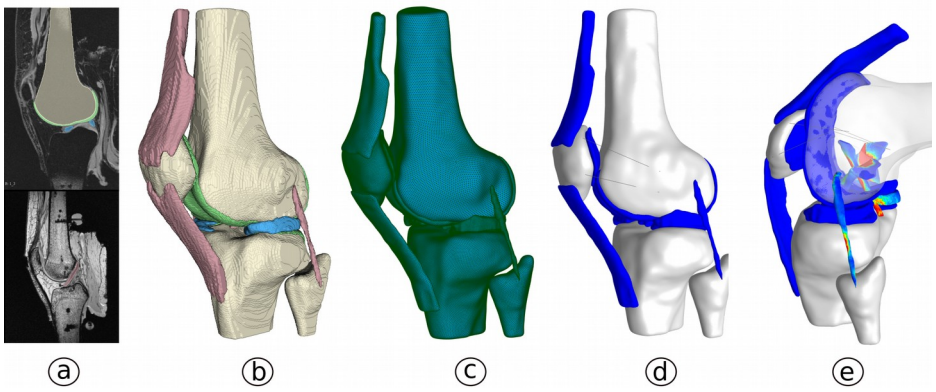

Figure 1. Development of virtual knees. a) tissue boundaries delineated from images, b) reconstructed geometry of all tissues of interest, c) mesh, d) template model, e) sample simulation of 90° passive flexion.

A cloud computing interface was previously built and integrated to the project site at SimTK. This platform currently allows the user to prescribe a desired tibiofemoral joint kinematics and simulations are performed on the sample femur-anterior cruciate ligament-tibia model. Additionally, to facilitate the use of joint mechanical testing data to run and validate the finite element models, Python scripts, for data extraction and simplification, were developed. These scripts can transform all the mechanical testing data to the image coordinate system as well as resample the data for ease of use with models. Further, a data share platform was integrated on the project site at SimTK to share all the raw and derivative data in a harmonized manner. Open Knee(s) raw and derivative data, and models will be ported to this system to provide project assets in a fully searchable manner based on editable metadata information.

An additional cohort of 13 knee specimens were also obtained through a synergistic collaboration. Imaging was performed and disseminated as per the Open Knee(s) specifications. An abridged set of joint testing data was also collected for each knee and will be disseminated.

Key Achievements

Segmentation, geometries and template models were generated for all 8 specimens and all the raw and derivative data were disseminated for public use. Imaging data for the additional 13 specimens were also disseminated. This publicly accessible comprehensive data will likely have a significant impact for modeling and simulation of specimen-specific knee joint behavior as the generation of model components, which is a labor intensive process, has already been completed.

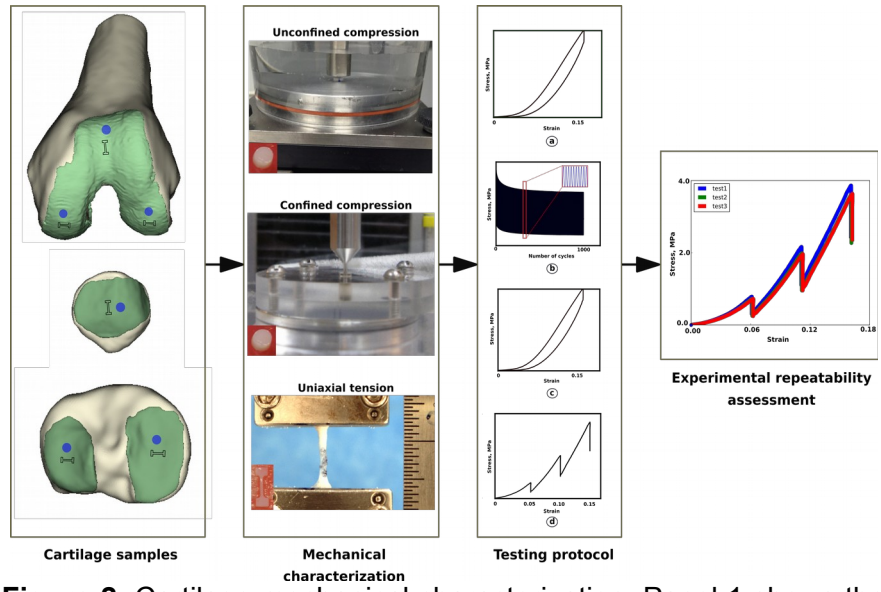

Figure 2. Cartilage mechanical characterization. Panel 1 shows the sample locations, panel 2 shows the various tests, panel 3 shows the testing protocol and panel 4 shows the three test repeatability data for stress relaxation.

A manuscript detailing the cartilage mechanical testing and the repeatability assessment was submitted to the Journal of Mechanical Behavior of Biomedical Materials. Manuscripts detailing the imaging and joint mechanical testing data were consolidated into a single manuscript that is currently in preparation for submission. An abstract detailing the development of 8 models was also accepted at the annual meeting of the Orthopedic Research Society to be held in 2020.

All the Generation 2 models were assembled and templated for simulating a 90° passive flexion. All models run at various capacity. Two models fully converged, one with in situ strain application. Rest of the models are being assessed and improved upon to converge fully (Figure 3). Generation 1 model was also updated to the latest version of the simulation software and disseminated publicly on the project site. All the scripts to analyse and transform the joint mechanical testing data to be in the image coordinate system as well as resampling the data for ease of use for comparison with the model output or use as model input, were also disseminated. These scripts will help users to simplify the joint mechanical testing data as obtained from the robot.

The Open Knee(s) project also provided data and specifications for another project titled *Reproducibility in Simulation Based Prediction of Natural Knee Mechanics* (R01EB024573, National Institute of Biomedical Imaging and Bioengineering, National Institutes of Health). This data set has been foundational for the activities of that project.

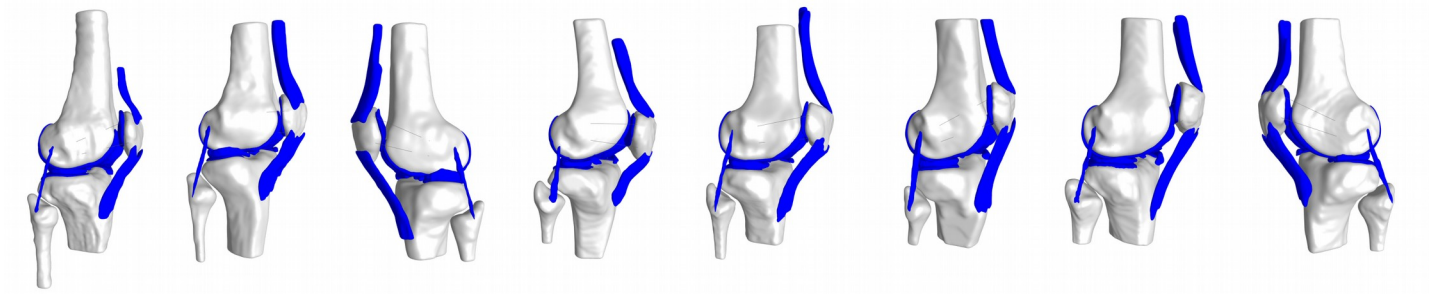

Figure 3. Finite element representations of all Open Knee(s) - Generation 2 specimens.