Open Knee(s) - Generation 2: A Virtual Specimen Cohort for Computational Knee Biomechanics

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INTRODUCTION: Computational modeling is an essential tool for understanding the basic science of joint/tissue function and to supplement modern clinical decision making. However, the needs for controlled image segmentation, registered mechanical data acquisition, software development tools, and the technical expertise make building such models costly and time intensive. Although a large number of finite element (FE) models of the knee have been described in the literature (1), there is a scarcity of *publicly available* fully protocol-referenced models, particularly with high anatomical and mechanical fidelity (2). FE models and protocols guided by FAIR principles (3) can be of significant value to both researchers and clinicians alike. Thus, the overall goal of the Open Knee(s) initiative is to build and disseminate a set of FE models of the knee with necessary supporting data. In Generation 1, we described a basic framework and an initial model generation process (2). In Generation 2, we present a cohort of eight specimen-specific knee joint FE representations supported by specimen-specific anatomical, and mechanical data. All the data, models and derivative data, e.g. segmentations, geometries, etc., that are generated through the modeling processes are publicly disseminated. This study presents this cohort and summarizes the current progress.

METHODS: Eight specimens from donors representing a wide population (Table 1) were used in this study*. Joint-level mechanical measurements and tests were performed on each specimen. Each specimen also underwent three magnetic resonance imaging (MRI) sequences resulting in five image sets. From these, segmentations of femur, tibia, patella, cartilages, menisci, quadriceps tendon, patellar ligament, anterior-posterior cruciates, and medial-lateral collateral ligaments were done (Figure 1a) using the open-source 3DSlicer software (https://www.slicer.org/) with geometries post-processed using Meshlab (http://www.meshlab.net/) (Figure 1b). A series of in-house Python programs were developed (provided) to automate FE mesh generation for template FE models in Salome (https://www.salome-platform.org) (Figure 1c and 1d). The template models were then customized for material properties and boundary conditions relevant to knee biomechanics. FE simulations of 90° passive flexion were done using FEBio (https://febio.org).

RESULTS: Three of the Generation 2 models (oks001, oks003, oks008) converged fully during simulations of 90° passive flexion. Three converged partially – oks002 (19% of 90° flexion), oks009 (48%), oks004 (64%) and two are in progress, oks006 and oks007. Preliminary stress patterns and ranges appear consistent within acceptable limits (Figure 1e).

DISCUSSION: Presented here is the Open Knee(s) Generation 2 specimen-specific cohort of 3D FE models of the knee (Figure 2). To our knowledge this is the most comprehensive cohort of knee models *publicly available*; with detailed specimen-specific anatomies, associated joint kinematics-kinetics biomechanical data, and all components of model development including segmentations, surface geometries, meshes, and so on. Improvements in all models are ongoing, e.g. troubleshooting for convergence, in situ strains, etc., and further calibration and benchmark studies using available joint mechanical testing data. Tissue samples from all specimens were also acquired and stored for ongoing specimen-specific characterization of material properties. While the size of this cohort is currently limited, further specimens (additional 13) are in progress. Availability of this sample population of virtual specimens can enable investigators to conduct virtual experiments, in lieu of physical testing, reducing the burden of building detailed models and providing guidelines for future knee-joint testing and analysis by us and others. Development is open and all the protocols, specifications, anatomical and mechanical data (MRI, joint and tissue mechanical testing), FE models, and intermediate information (segmentations, geometries and meshes) is disseminated freely for any type of use (academic or commercial) at: https://simtk.org/projects/openknee.

SIGNIFICANCE/CLINICAL RELEVANCE: Developing robust, specimen-specific FE knee models can significantly enhance both basic research and patient-specific clinical decision making—with applications to custom implant/prosthetic design, surgical planning, and related. This database can enable progress in model generation and analyses, potentially improving patient-specific analysis turnaround. Validated models with efficient, documented protocols can also serve as effective tools for studying healthy and pathological joint mechanics and enable analysis of wider population cross-sections. Such models can also be leveraged for medical training.

REFERENCES:
1. Kazemi et. al. *Recent Advances in Computational Mechanics of the Human Knee Joint.* Comp and Mathematical Methods in Medicine, Volume 2013.
2. Erdemir A. *Open Knee: Open Source Modeling & Simulation to Enable Scientific Discovery and Clinical Care in Knee Biomechanics.* Journal of Knee Surgery, 2016 Feb.
3. https://www.go-fair.org/fair-principles/

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Table 1: Specimen properties and donor demographics (all Caucasian)

Specimen	oks001	oks002	oks003	oks004	oks006	oks007	oks008	oks009
Side	right	right	left	right	right	right	right	left
Gender	male	female	female	female	female	male	male	male
Age (years)	71	67	25	46	71	71	40	34
Height (m)	1.83	1.55	1.73	1.58	1.52	1.7	1.78	1.8
Weight (kg)	77.1	45.3	68	54.4	49.4	65.8	63.5	68.03
BMI	23.1	18.9	22.8	21.9	21.3	22.7	20.09	20

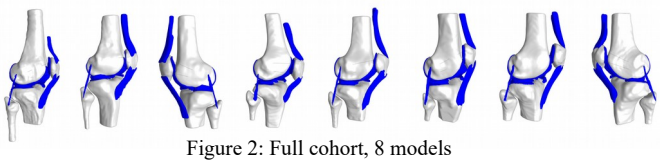

Figure 2: Full cohort, 8 models

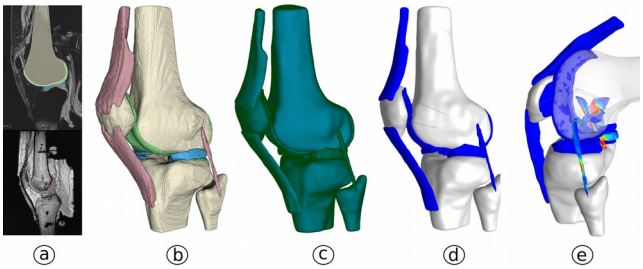

Figure 1: Development of FE model (spec: oks003) with a) MRI segmentation, b) raw geometry, c) FE multi-component meshes, d) assembled model, e) preliminary simulation results

*This study was exempt from Institutional Review Board review as the tests were conducted on cadaver specimens and donor information was de-identified by the supplier.