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OPEN KNEE(S): MAGNETIC RESONANCE IMAGING FOR SPECIMEN-SPECIFIC NEXT GENERATION KNEE MODELS

C.J. Bennetts (1,2), S. Chokhandre (1,2), S.B. Donnola (3), C.A. Flask (3,4,5,6), T.F. Bonner (1,7), R.W. Colbrunn (1,7), A. Erdemir (1,2)

(1) Department of Biomedical Engineering
(2) Computational Biomodeling (CoBi) Core
(7) BioRobotics and Mechanical Testing Core
Lerner Research Institute
Cleveland Clinic
Cleveland, Ohio, USA

(3) Department of Radiology
(4) Department of Biomedical Engineering
(5) Department of Pediatrics
(6) Case Center for Imaging Research
Case Western Reserve University
Cleveland, Ohio, USA

INTRODUCTION

Magnetic resonance (MR) imaging is a modality that is ideally suited for computational modeling of musculoskeletal joints due to its ability to non-invasively represent the three-dimensional morphology of various osseous and soft tissue structures. When using cadaver specimens, the joints are left intact allowing mechanical testing after imaging for experimental validation. Therefore, it is not surprising that magnetic resonance imaging (MRI) has been commonly used in many prior knee joint modeling and simulation studies. The knee contains several different soft tissue structures that are essential to represent anatomically and mechanically in order to accurately understand knee biomechanics using finite element (FE) analysis. These structures, including bone, cartilage, tendons, ligaments and menisci, have varying molecular compositions that influence their contrast in MR imaging. MRI is a complex imaging modality, which must be properly tuned in order to adequately identify these various tissues of interest. Currently, optimal MRI protocols for knee modeling studies have not been thoroughly evaluated. The most comprehensive prior knee modeling studies [1,2] have typically included limited sets of MR scanning settings, most likely due to convenience or other constraints, which may compromise the appropriate acquisition and representation of tissue morphology, and therefore the overall biomechanical response of the knee joint as predicted by computational modeling.

This study is part of a more comprehensive project, called Open Knee(s), which aims to generate a set of fully specimen-specific knee models, including morphology, tissue-specific material properties, and experimental joint kinematics-kinetics responses, for a sample of male and female, young and elderly, and healthy and osteoarthritic cadaveric samples. The specific goal of this study was to identify and utilize a set of MR imaging protocols on Open Knee(s) specimens that are better suited for the development of the next generation of knee models.

METHODS

The Open Knee(s) project aims to include a minimum of ten knee specimens in order to describe a cross-sectional sample of the population, consisting of male and female, young (18-35 years) with healthy cartilage, elderly (65-80 years) with healthy cartilage, and elderly with osteoarthritic cartilage (moderate, based on Kellgren-Lawrence grading [3,4]). The other requirements of the individuals from which specimens were obtained include: height (1.5-1.8 m), weight (45-90 kg), and Body Mass Index (BMI) (18.5-24.9 considered the normal range). In the current work, five specimen were imaged; four matching the aforementioned specifications and another with an age of 46 years.

The hard and soft tissue structures that are necessary to incorporate in an FE model in order to accurately simulate the mechanical response of the knee joint include the bones (femur, tibia, patella), their cartilage, the quadriceps tendon, major ligaments and menisci. The underlying shape of the bones provides the contours through which loads on the joint are transferred and distributed through contact between the articulating surfaces of the cartilage in the tibiofemoral and patellofemoral joints of the knee. The cartilage exhibits a multiphasic, rate-dependent mechanical response governed by interactions between its solid, fluid, and ionic phases, which act to resist, absorb, and distribute joint loads and reduces friction within the joint. The ligaments (anterior and posterior cruciate, medial and lateral collateral, and patellar) provide joint stability through tensile engagement and act to limit the range of motion for different degrees of freedom within the joint. The menisci conform to the opposing surfaces of the articular cartilage of the femur and tibia to provide stability during knee flexion. Geometric reconstruction of all these tissues is therefore important to develop mechanically authentic models. The tissue types of interest have varying molecular compositions, each with distinct electromagnetic resonance signatures that influence the strength of the signal intensity with respect to the particular MRI settings. Therefore, different MR scanning protocols are required to best delineate the boundaries of each tissue type within the knee.

Initial MR settings to highlight each tissue type were obtained from a study through the osteoarthitis initiative (OAI), sponsored by the National Institutes of Health (NIH) [5]. A series of imaging trials were undertaken to refine these initial protocols to best delineate the desired knee structures. The goals in tuning the MRI parameters were to increase resolution and tissue contrast, to accommodate a total image acquisition time of less than 2 hours, and to adapt to the particular MRI machine being used. A resulting set of three different MRI protocols were developed with the intention to identify: 1) all structures simultaneously for general-purpose reference, 2) cartilage and possibly menisci, and 3) ligaments, tendons, and possibly menisci. The general-purpose imaging protocol was a 3D T1-weighted sequence *without* fat suppression having an isotropic resolution of 0.5 mm, echo time (TE) of 6.01 ms, and repetition time (TR) of 20 ms. The cartilage imaging protocol was a 3D T1-weighted sequence *with* fat suppression having an anisotropic resolution of $0.35\times0.35\times0.7$ mm, TE of 5.34 ms, and TR of 29 ms. The ligament and tendon imaging protocol was a proton-density, turbo spin echo sequence with an anisotropic resolution of $0.35\times0.35\times2.8$ mm, TE of 9.7 ms, and TR of 10,000 ms. The ligament and tendon imaging protocol was acquired in three orientations, with the high-resolution in-plane dimension lying in the axial, sagittal and coronal planes of the knee. The reference coordinate systems remained the same for all three scanning protocols, which will allow the components of the knee model to be defined from the associated image sequence and easily recombined. Knee specimens were transported and imaged in a custom designed, cylindrical acrylic tube, supported along the axis with foam discs with tension applied to the quadriceps tendon to ensure it was lightly engaged (not slack). MR images were acquired using a Siemens Magnetom Skyra 3 Tesla MRI machine in the Department of Radiology at the Case Western Reserve University, Cleveland, Ohio.

Another aspect of the imaging procedure that was necessary for modeling and simulation involves appropriately orienting the knee joint geometry, derived from the MR images, with respect to the follow-up experimentation on joint kinematics-kinetics [6]. To accomplish this, three spherical, MRI-opaque markers were rigidly fixed to the femur and tibia. For the patella, a custom 3-D printed fixture (with three spherical, MRI-opaque markers) was fixed to the bone. The centers of these spheres can be calculated from surface coordinates of the spherical geometry from MRI, and from mechanical testing, to accurately align imaging and mechanical testing coordinate systems.

RESULTS

Figure 1 shows a mid-sagittal slice from the isotropic general-purpose imaging sequence for the currently scanned set of knee specimens, highlighting the variations in morphology that exist in our sample population.

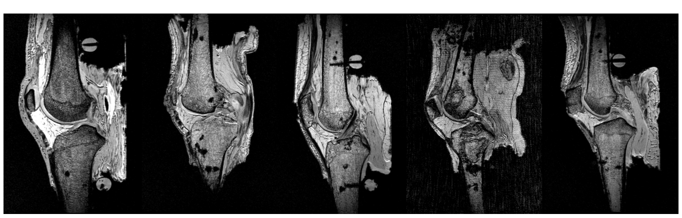

Figure 1. General purpose imaging for five cadaver specimens.

To illustrate the potential role that the selected MR protocols have on delineating the different soft tissue structures within the knee, Figure 2 includes the complete set of scans for a single specimen, identifying the corresponding structures of interest for which the particular sequence was performed. Figure 2 also shows the boundary of a spherical, MRI-opaque markers as it appears in the isotropic, general purpose MR image.

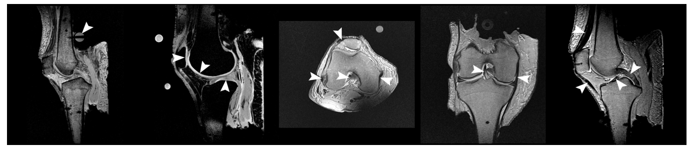

Figure 2. All imaging sequences for development of knee models. From left to right: Panel 1 – general purpose imaging; registration marker is highlighted. Panel 2 – cartilage imaging; femoral, tibial, and patellar cartilage are highlighted. Panels 3-5 – ligament and tendon imaging; cruciate, collateral, and patellar ligaments are identified along with their insertions.

DISCUSSION

A comprehensive set of MRI protocols were devised in order to represent various structures of the knee with particular emphasis on their incorporation in FE models. The imaging data acquired using this comprehensive set of refined MR protocols will likely allow a more accurate morphological representation of the associated soft-tissue structures, thereby reducing the potential error in the biomechanical response of their prospective models.

Ideally, the higher the resolution of the MR images, the more accurately the geometric boundaries of the tissue structures can be represented. Given the MR scanner and protocols that were used, the resolutions of the images obtained were as high as possible. However, using other MR scanners or through advances in MR imaging technology, higher fidelity geometric models may be possible.

The presented specimens have already undergone joint kinematics-kinetics testing [6] and tissue characterization is in progress. In the near future, the remainder of the Open Knee(s) specimens will be imaged and experimentally tested. Once image data has been acquired for all specimens, the associated knee models will be generated, which includes segmenting the tissue structures of interest from the MR images to identify their boundaries, and then meshing this geometry to determine an adequate mesh density to ensure mechanical convergence. Once the finite element models are obtained, they can be combined with experimental data describing the relative movements of the joints [6], resulting from various conditions prescribed during experimental testing, in order to evaluate the predictive capacity of the models. This significant amount of heterogeneous data is acquired openly and will be made available to the community through the Open Knee(s) project. Utilization of these data to develop and extend the next generation of fully specimen-specific models will provide unique opportunities not only for us, but for others as well, for yet-unknown applications in the study of healthy and osteoarthritic knee joint function.

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REFERENCES

[1] Mootanah, R et al., *CMBBE*, 17:13, 1502-17, 2014.
[2] Kiapour, A et al., *J Biomech Eng*, 011002-1-14, 2014.
[3] Berger, MJ et al., *Arthritis Care Res*, 64(5):729-34, 2012.
[4] Braun, HJ et al., *Bone*, 51(2):278-88, 2012.
[5] Peterfy, CG et al., *OA & Cart*, 16:1433-41, 2008.
[6] Bonner, TF et al., *SB^{3}C, 2015.*