INTRODUCTION

The substructures of the tibifemoral joint significantly affect the mechanics of the joint. It is necessary to have a better understanding of the multiscale mechanics of the joint in order to develop treatment options and preventative measures for knee joint injuries and pathologies. With the growing focus on simulation studies of the knee joint for scientific and clinical purposes [1,2], data for model development and verification is becoming increasingly important. This is particularly important in instances where finite element (FE) analysis is used for clinical decision making.

Many studies employing FE analysis of the knee joint rely on literature for material properties and have limited validation, which may or may not be adequate to accurately represent the phenomena of interest. Expanding upon our previous study [3], where specimen-specific imaging and joint level mechanical testing data was acquired, this study aims to acquire specimen-specific tissue level mechanical response as well as cellular level information via histological analysis. This detailed dataset will provide complete multiscale information for development and confirmation of multi-resolution, finite element models to better understand the effects of macro (joint) level occurrences on micro (cell) level behavior.

METHODS

Mechanical testing was performed on a cadaver knee (34 year old female, normal BMI, no knee or foot injury, surgeries, osteoarthritis or inflammatory arthritis). The joint level testing was described previously [3] and is summarized here. The specimen was prepared such that only femur, tibia, femoral and tibial articular cartilage, anterior and posterior cruciate ligaments (ACL and PCL), medial and lateral collateral ligaments (MCL and LCL), and menisci were intact. Magnetic resonance (MR) images were acquired using a 4 Tesla scanner (Medspec, Bruker Biospin Corp., Billerica, MA) (Fig. 1). Mechanical testing of the joint was conducted on a six degrees of freedom (DoF) motion control robot (Rotopod R-2000, Parallel Robotic Systems Corp., Hampton, NH, USA) (Fig. 1). Laxity and combined loading tests were performed for flexion angles ranging from 0° to 90° in 30° increments.

Following joint testing, the substructures were dissected and tissue mechanical testing samples were prepared. Overall 12 samples were tested from femoral and tibial articular cartilage, cruciate and collateral ligaments and the menisci. Five mm diameter, full thickness cartilage and meniscus samples were tested under confined compression. Meniscus samples were also tested in uniaxial tension (dumbbell shaped, 5mm by 1mm test length). Ligament samples were tested under uniaxial tension (dumbbell shaped, 10mm by 2mm test length). All the tests were conducted on a uniaxial material testing system (MTS Systems Corporation, Eden Prairie, MN, USA). All the specimens were immersed in a saline bath and kept at 37 °C during testing. Stress relaxation tests were performed on all samples. Each cartilage and meniscus sample was tested at 5%, 10% and 15% strain at 20%/s strain rate for both confined compression and uniaxial tension. A preload of 0.05N was applied before the stress relaxation to obtain the initial test length of the cartilage and meniscus samples. In case of ligaments a preload of 0.1 N was applied followed by 10 preconditions cycles at ± 0.25 mm. A stress relaxation test was performed at 5% and 10% strain at 20%/s strain rate.
for all the ligament samples. Histology slides (H&E staining) were also prepared for all the tissue types.

RESULTS

The MR images and the joint testing data provided adequate specimen-specific anatomical information and mechanical response for joint level model development and evaluation (Fig. 1). The tissue testing data will be useful in specimen-specific tissue characterization, which in turn can be utilized to establish specimen-specific material properties in computational models (Fig. 2). Figure 3 shows the sample histology for femoral articular cartilage, ACL and medial meniscus.

DISCUSSION

The aim of this study was to obtain comprehensive multi-resolution mechanical testing and imaging data for the tibiofemoral joint, which can be used for the development of specimen-specific multiscale FE models of the joint. The study is first of its kind to obtain data at several spatial levels for a single specimen. Joint scale models can be developed based on specimen-specific anatomy. Specimen-specific material properties (cartilage, menisci, and ligaments) can be obtained from tissue mechanical testing. Experimental joint kinetics and kinematics can be used as an independent dataset for confirmation of model predictions. Histology data can be utilized to develop cell-scale models, again specific to the specimen. While this information provides significant value for simulation based—medicine, some limitations are apparent in its scope; only one specimen was tested, some tissue components (which may be of interest for other purposes) were removed prior to joint testing including the patella, and the total number of tissue testing samples were limited.

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