OPEN KNEE(S): COMPREHENSIVE PATELLOFEMORAL JOINT TESTING FOR SPECIMEN SPECIFIC NEXT GENERATION KNEE MODELS

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INTRODUCTION

Developing virtual knee models for clinical and scientific simulations of the patellofemoral joint requires evaluating their predictive capacity, to represent physiological joint kinematics-kinetics and contact mechanics, in order to establish model credibility [1]. With comprehensive testing, specimen-specific models can be developed to represent not only individualized anatomy, but also tissue mechanical properties. In addition, with joint level mechanical testing data, the accuracy of the model can be confirmed.

Recently, the Open Knee(s) project has been launched to mitigate various uncertainties in modeling and simulation of the knee joints with the aim to build completely specimen-specific (geometry and material) three-dimensional finite element representations from different populations with varying gender, age and grades of osteoarthritis [1]. Within this project's framework, specimen-specific patellofemoral joint mechanics have been measured such that specimen-specific evaluation of model performance can be conducted in an elaborate manner. The goal of this document is to provide the specific details of the patellofemoral testing within the framework of the Open Knee(s) project.

METHODS

Six knee specimens were obtained (Table 1). All specimens were absent of knee injury, surgeries or inflammatory arthritis. A specimen preparation protocol allowed placement of optoelectronic measurement sensors (Optotrak, Northern Digital Inc., Waterloo, Ontario, Canada) and registration markers (to relate mechanics data to imaging) on the tibia, femur, and patella.

Table 1: Specimen Characteristics

Specimen #	Gender	Age	Height	Weight	BMI
oks001	Male	71	1.83 m	77.1 kg	23.1 kg/m^2
oks002	Female	67	1.55 m	45.3 kg	18.9 kg/m^2
oks003	Female	25	1.73 m	68.0 kg	22.8 kg/m^2
oks004	Female	46	1.58 m	54.4 kg	21.9 kg/m^2
oks006	Female	71	1.52 m	49.4 kg	21.3 kg/m^2
oks007	Male	71	1.7 m	65.8 kg	22.7 kg/m^2

Anatomical landmarks and MRI-opaque registration spheres were digitized relative to the optoelectronic sensors, respectively, on the tibia, femur and patella and standardized joint coordinate systems (JCS) were created and defined for the tibiofemoral and patellofemoral joints [2]. The specimen was then secured to the robotic Universal Musculoskeletal Simulator [3], capable of six degrees-of-freedom and real-time force feedback using simVITRO^{TM} software (Cleveland Clinic, Cleveland OH). The tibia was secured to two 6 DOF force-torque sensors (SI-1900-80, ATI Industrial Automation, Apex, NC) embedded in a custom stage rigidly attached to the robot. These sensors were used to measure force vectors applied to the tibia by the femur and provide feedback needed to drive the robot. A quadriceps loading system was developed utilizing a Baldor (Fort Smith, AR) model BSM80N-275AE servomotor and a harmonic drive system (CSG-40-50, Hauppauge, NY). The quadriceps tendon was held by a custom wire mesh grip (DCD Design and Manufacturing Ltd., Richmond BC, Canada) and frozen with liquid nitrogen. Quadriceps loading was applied under force feedback control synchronized with the robot to achieve a desired joint loading state.

A Tekscan (Boston, MA) sensor (5051, 1,200 psi range) was inserted in the patellofemoral joint to measure contact mechanics.

Patellofemoral mechanics were characterized under quadriceps loading at tibiofemoral flexion angles of 0°, 15°, 30°, 45°, and 60°. At each flexion angle the tibiofemoral joint was set to a position approximating passive flexion (20 N quadriceps, 20 N tibiofemoral compression, and all other off-axis loads minimized). Then, quadriceps loads were applied at 20, 100, 200, 300, 400, 500, and 600 N. At each loading state, the patellofemoral contact mechanics, patellofemoral kinematics, tibiofemoral kinematics, and tibial loads were measured.

RESULTS AND DISCUSSION

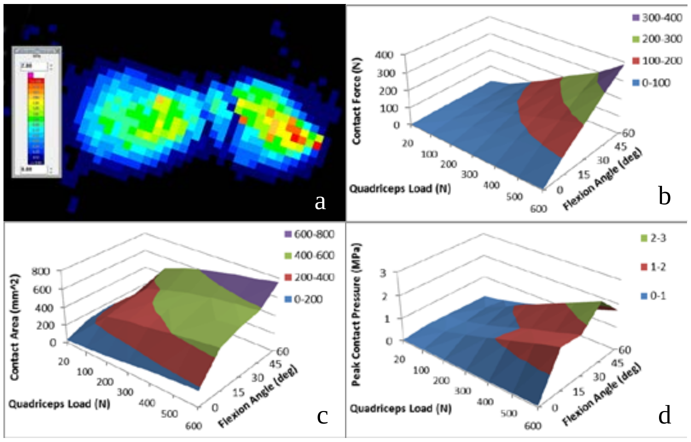

Figure 1: Patellofemoral contact mechanics for oks007 specimen. a) pressure distribution at 60° flexion and at 600 N quadriceps force, b-d) contact force, area, and peak pressure at all flexion angles and loading conditions, respectively.

For the purpose of this abstract, one specimen's results were highlighted. Patellofemoral contact mechanics for a single specimen (oks007) are shown in Figure 1. The pressure distribution at 60° flexion with a 600 N of quadriceps load a dual contact area is shown in Figure 1a. The contact force and area increased with both flexion and quadriceps loading and the peak contact pressure monotonically increased with quadriceps loading (Figures 1b-d), but not with flexion. The highest contact pressure recorded for this specimen was at 45 degrees of flexion. Table 2 illustrates the variability of peak contact pressure across specimens at this same loading condition.

Table 2: Peak contact pressure for each specimen at 45 degrees of flexion and 600 N of quadriceps load.

Peak Contact Pressure (MPa)					
oks001	oks002	oks003	oks004	oks006	oks007
1.76	2.90	2.90	2.22	3.37	2.61

In order to build virtual knee models with accurate specimen-specific joint mechanics, the model predicted joint kinematics-kinetics and contact mechanics should be similar to the experimental measurements for the corresponding specimen. This document outlined the specific details on how patellofemoral testing was completed within the framework of the Open Knee(s) project to provide the opportunity for specimen-specific evaluation. Anatomical images and tissue properties were also collected for the same specimens as part of the Open Knee(s) initiative, aiming to build geometric and mechanically consistent specimen-specific models.

When specimen-specific patellofemoral joint mechanics data are not available, data from the literature can be utilized. However, it is evident that contact mechanics vary largely amongst specimens and such comparisons may suffer from uncertainties associated with anatomical and mechanical variations between specimens (Table 2).

Open Knee(s) project targets to complement the reported data by testing four additional specimens, to further diversify the population of patellofemoral joint data. The next steps involve development of specimen-specific knee models to evaluate against the contact mechanics data collected in this study, for each respective specimen. These models can then be used by any and all interested investigators to further elucidate patellofemoral pathologies and potential treatment options for patients.

ACKNOWLEDGMENTS

This study was funded by NIGMS, NIH (R01GM104139, PI: Erdemir). Assistance from Katie Stemmer, Dylan Beckler, Sam Doerle and Erin Merico is appreciated. Open Knee(s) is an open development modeling project; specifications, models, and data can be accessed at http://wiki.simtk.org/openknee.

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