The Development and Implementation of a Computational Framework to Simulate Patellofemoral Joint Mechanics: Direct Comparisons Between Musculoskeletal Modeling and Finite Element Analysis

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INTRODUCTION: Anterior knee pain is a multifactorial condition with a high prevalence (~25% of the general population) [1]. Altered tracking and loading of the patellofemoral joint (PFJ) are associated with anterior knee pain [2], but it remains unclear exactly how factors such as muscle weakness or abnormal anatomy (e.g., excessive femoral anteversion or patellar malalignment) impact PFJ mechanics and contribute to anterior knee pain. Experimental approaches such as cadaveric studies are limited by cost, time, and logistical challenges, and *in vivo* studies are limited to non-invasive or minimally invasive methods that are not able to directly measure tissue and joint mechanics. Computational modeling provides a non-invasive approach to studying joint biomechanics, with Finite Element Analysis (FEA) and Musculoskeletal (MSK) modeling as two common approaches. MSK models can provide rapid simulations of whole-body movement with varying degrees of subject-specificity, while FEA provides more tissue-level detail assessment at a higher computational cost. While both modeling approaches have been used previously to study patellofemoral joint biomechanics, direct comparisons between MSK and FEA models are needed to guide the implementation of such models. The goals of this project are to: 1) establish, for the first time, a workflow that provides direct comparison between MSK and FEA modeling of the patellofemoral joint, and 2) assess the extent to which specific MSK and FEA model outputs are correlated. We hypothesized that MSK joint loads would correlate with FEA cartilage stress in simulations of a healthy individual.

METHODS: Marker-based motion capture was performed on one adult male subject (35 years, 180 cm, 82 kg) with a 12-camera VICON system (52 total reflective markers) and two AMTI force plates (Figure 1A). The study was approved by the Bucknell University IRB (study number 2324-118), with a multi-subject dataset of equal sex participants ongoing. A self-selected walking trial and a neutral bodyweight squat trial were collected, among other trials, for future work. The LaiUhlrich2022 OpenSim model was used as a baseline MSK model and scaled to the participant [3], with modification of the vastus medialis muscle path based on anatomical literature to improve the physiological accuracy of muscle force directions (Figure 1B) [4, 5]. Kinematics and kinetics were computed using OpenSim Moco, an optimal control tool [6]. MocoTrack was used to track marker trajectories and generate joint kinematics, which were then prescribed via a MocoInverse along with experimental ground reaction forces to generate kinetics. Patellofemoral joint loads were then computed using the joint reaction analysis tool. Optimization weights were adjusted to ensure accurate muscle activity patterns and reduce residual pelvis actuators. A finite element model of the left patellofemoral joint was developed in Abaqus using the OpenKnee [7] (OKS009) geometry (Figure 1C). The femur, tibia, and patella were modeled as rigid bodies, femoral and patellar cartilages as hyperelastic neo-Hookean materials, and the medial/lateral patellofemoral ligaments and patellar tendon were modeled as nonlinear spring connectors. The femur was fixed, tibial boundary conditions applied, and quadriceps forces applied to the patella. A custom MATLAB script calculated quadriceps muscle unit vectors and tibial kinematics from MSK models and full MOCO solutions, while aligning the OpenSim and OpenKnee frames to ensure consistency (Figure 1C).

RESULTS: During walking, maximum activation occurred in mid-stance (17° knee flexion) with vastii activation of approximately 10-12% of maximum contraction. In squatting, maximum activation occurred during the eccentric phase, with vastii activation of approximately 50%. Peak patellofemoral joint reaction force (PFJRF) from the MSK model reached 6.47×BW at 100° knee flexion during squatting, compared to 0.71×BW during late stance in walking. PFJRF and maximum cartilage von Mises stress from the FEA model increased with greater knee flexion angles (R^2=0.95, Figure 1D). Deeper squats were also associated with larger cartilage contact areas, with more contact observed on the lateral facet (Figure 1D).

DISCUSSION: This study established a workflow of musculoskeletal and finite element modeling to evaluate patellofemoral joint mechanics during functional tasks. The workflow enables direct comparison of PFJ mechanics between simulation types. Results supported our hypothesis, showing that higher PFJ reaction forces from MSK simulations were accompanied by greater cartilage stresses in FE models of healthy squatting. Patellar cartilage contact area also increased with flexion (Figure 3D), aligning with in vivo PFJ contact area measurements reported by Guan et al. (2024) [8]. Predicted PFJRF distributions and peak values were consistent with prior reports for walking and squatting [9, 10]. A limitation of this study is a sample size of n=1, with further experimental data collection and simulation work currently ongoing. This framework can be extended to simulate pathological conditions and abnormal lower-limb anatomies – such as muscle weakness or altered torsional alignment – thereby enabling large-scale simulations across diverse scenarios to develop more detailed relationships between joint loading patterns and cartilage stress measures.

SIGNIFICANCE/CLINICAL RELEVANCE: By linking estimates of joint loading from musculoskeletal models with predictions of cartilage stress from finite element simulations, this study provides a computational framework to study patellofemoral mechanics and identify movement-related contributors to anterior knee pain. Establishing consistent relationships between outputs from both modeling approaches would allow researchers and clinicians to assess the biomechanical consequences of specific interventions for anterior knee pain. Ultimately, such correlations could support the development of low-cost, patient-specific, non-surgical treatment strategies by linking observable movement adaptations to internal joint and cartilage stress profiles.

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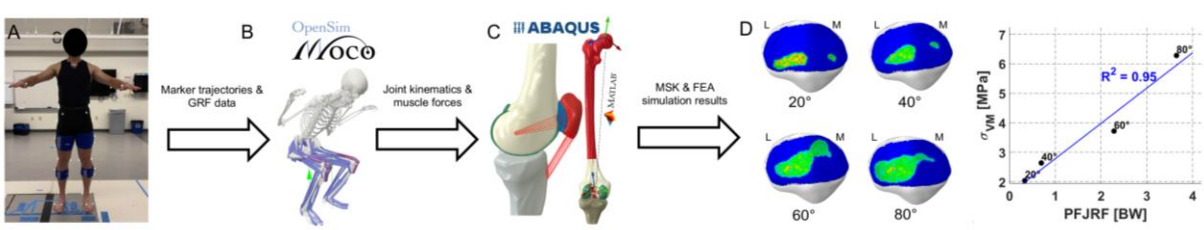

Figure 1. A) Motion analysis participant and marker set. B) OpenSim Moco MSK simulation, with activated quadricep muscles shown in red. C) FEA model of the patellofemoral joint, with alignment of the OpenSim and OpenKnee frames to ensure consistency in kinematic definitions. D) Simulation results, showing cartilage contact pressure at different knee angles during squat and correlations between MSK model joint load and FEA model von Mises stress.