EFFECTS OF QUADRICEPS FORCE VARIABILITY ON PATELLOFEMORAL CARTILAGE STRESSES

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INTRODUCTION

Elevated stresses at the cartilage-bone interface is a possible mechanism for patellofemoral (PF) pain. Cartilage stress at the PF joint is influenced by quadriceps forces, which vary between subjects and are difficult to estimate. It is unclear how susceptible cartilage stresses are to uncertainty in muscle forces. Previous studies have combined electromyography (EMG)-driven musculoskeletal modeling with finite element (FE) analysis to quantify cartilage stresses [1, 2]. We have developed a probabilistic FE modeling framework incorporating uncertainty in muscle forces to predict distributions of contact area, hydrostatic pressure and octahedral shear stress at the cartilage-bone interface. This framework was applied to 7 subject-specific models, and cartilage contact area and stresses, and their sensitivity to muscle forces were evaluated.

METHODS

Quasi-static PF FE models of 7 subjects (2 healthy, 5 PF pain) were developed to simulate loads during a weight-bearing squat [1]. High-resolution Magnetic Resonance (MR) images (1.5T, GE Healthcare, Milwaukee, WI) were used to create surface geometry. Bones were modeled as rigid 4-noded shell elements and cartilage was represented as 8-noded linear elastic (E = 7 MPa, ν = 0.47) hexahedral elements [1]. One-dimensional tension-only elements were used to represent the patella ligament and quadriceps muscles. The meshes were registered to open configuration MR images (0.5T GE Signa SP, GE Healthcare, Milwaukee, WI) of the knee at 60° flexion during an upright, weight-bearing squat (Figure 1a). The tibia and femur were fixed and quadriceps forces were predicted from an EMG-driven musculoskeletal model [3].

Probabilistic methods were incorporated using NESSUS (Southwest Research Institute, San Antonio, TX) to evaluate the effects of uncertainty in EMG-derived muscle forces. Forces in different compartments of the quadriceps [1] were normally distributed, and means and standard deviations (SD) were based on multiple measurements of EMG activity during a static squat. The model predicted bounds (1-99 percentiles; ± 2.33 SD) of PF contact area, peak hydrostatic pressure (HP) and octahedral shear stress (OSS) at the bone-cartilage interface, and their sensitivity to applied muscle forces.

RESULTS AND DISCUSSION

Predicted size of 1-99% bounds for patella cartilage shear stress varied from 0.007 MPa (Subject 6) to 1.21 MPa (Subject 4), representing 0.4% and 77.2% of their respective mean values (Table 1). Bounds of patella cartilage pressure varied from 0.45 MPa (Subject 1) to 6.05 MPa (Subject 5), representing 14.6% and 117.3% of their respective mean values (Table 1, Figure 1b,c). Patella contact area varied by up to 24.6% of mean (not shown), while femur cartilage shear stress and pressure varied by up to 77.3% and 57.6% of their mean values, respectively (not shown). Stresses in the patella cartilage were most sensitive to vastus lateralis muscle force, and least sensitive to rectus femoris muscle force (not shown).

The study demonstrates differences in cartilage stress response between subjects to variable muscle force application. Modeling uncertainty in forces calculated from multiple measurements of EMG activity during a static squat resulted in minimal (0.4% in OSS for Subject 6) to substantial (117.3% in HP for Subject 5) changes in cartilage stresses and pressures (Table 1); variations in PF joint geometry, cartilage thickness, and muscle fiber orientations may explain some of these differences. Understanding the mechanisms responsible for cartilage stress may lead to greater insight into the causes of PF pain.

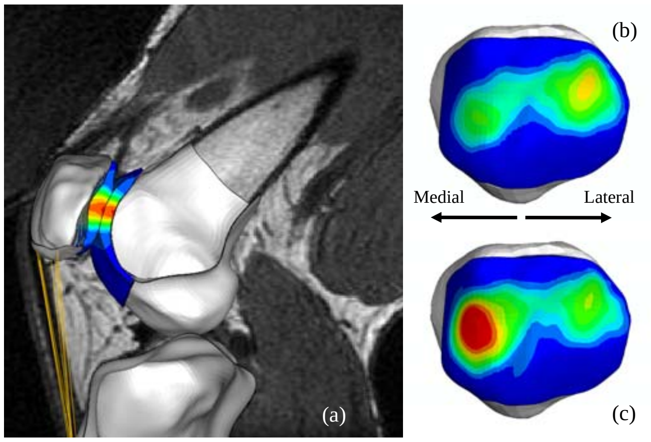

Figure 1: Subject-specific FE model from weight-bearing MR images of a squat cycle (a), and representative patella cartilage pressures for 1% (b) and 99% (c) bounds.

Table 1: Mean and bounds (MPa), and % change (compared to mean) in patella subchondral stresses. Subjects 1 and 2 were healthy, and 3 to 7 had PF pain.

#	Octahedral Shear Stress				Hydrostatic Pressure			
	Mean	Min	Max	%Chg	Mean	Min	Max	%Chg
1	1.35	1.07	2.06	73.0	3.10	2.86	3.31	14.6
2	0.94	0.76	1.24	51.4	2.28	2.05	2.52	20.5
3	1.51	1.24	1.90	43.4	4.60	3.73	5.43	37.0
4	1.57	1.20	2.41	77.2	4.18	3.73	5.25	36.4
5	1.992	1.986	2.017	1.6	5.15	3.84	9.89	117.3
6	1.830	1.828	1.835	0.4	6.43	5.50	10.40	76.3
7	1.28	1.10	1.70	47.0	4.87	3.97	6.86	59.4

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