

Effects of Bone Deformation on Patient-Specific Finite Element Predictions of Hip Chondrolabral Mechanics

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INTRODUCTION: Hip osteoarthritis (OA) involves progressive cartilage degradation and subchondral bone changes, with joint loading and morphology playing key roles in disease progression¹. Patient-specific finite element (FE) models offer the ability to analyze chondrolabral (cartilage and labrum) mechanics, but predictions are sensitive to boundary conditions, tissue constitutive models, and bone material representation. In FE models, bone has been represented using heterogeneous subject-specific properties, homogeneous cortical-trabecular assemblies, shell elements, or rigid bodies, with trade-offs between physiological accuracy and computational cost. Despite the computational efficiency of rigid bone models, prior work suggests they may overestimate joint contact stresses due to lack of acetabular compliance². Recent advances, including physiologically accurate cartilage models, quadratic tetrahedral elements, and subject-specific kinematics and kinetics, have improved FE predictions of hip stresses and strains, warranting re-evaluation of the use of rigid bones in FE models of the hip³. Motivated by these developments, this study aimed to evaluate the influence of pelvis and femur material representation on FE predictions of chondrolabral mechanics during level walking and squatting. We hypothesized that rigid bone models would produce higher contact stresses and strains compared with models using subject-specific bone properties.

METHODS: Four male subjects (N=4, mean age: 23.3 ± 1.0 years, mean weight: 74.6 ± 9.7 kg, anterior posterior alpha angle: 46.8 ± 8.1) were selected from a prior cohort of eighteen individuals for patient-specific modeling. These specific subjects were chosen from the cohort because motion capture data were available for both level treadmill walking and squatting. Volumetric computed tomography arthrography (CTA) was acquired under traction, and images were segmented in Amira to generate surfaces of the cartilage layers, labrum, cortical bone, and trabecular bone for the hemipelvis and proximal femur. To investigate the effects of bone deformation on FE predictions, the pelvis and femur were modeled using four material representations (Figure 1A): (1) rigid bodies, (2) subject-specific inhomogeneous properties derived from CTA voxel intensity, (3) two homogeneous materials (cortical and trabecular bone), and (4) a single homogeneous material per bone. Acetabular and femoral cartilage were represented as inhomogeneous, anisotropic, hyperelastic materials with depth-dependent collagen fiber orientation, while the labrum was represented as transversely isotropic hyperelastic with circumferential fibers⁴. Subject-specific joint reaction forces and kinematics were used to drive FE simulations in FEBio (www.febio.org). Walking was analyzed at heel-strike (HS), foot flat (FF), midstance (MS), and heel-off (HO); squatting was analyzed at standing, 25%, 50%, 75%, and 100% of deep flexion (DF). Contact pressure and 1st principal Lagrange strain were evaluated on the acetabular cartilage, maximum shear stress was evaluated at the osteochondral interface, and contact pressure, strain, and shear stress were evaluated on the labrum. Contact area was evaluated across the cartilage and labrum contact interface. Computing time and peak memory usage were compared. Repeated-measures two-way ANOVAs assessed effects of bone material representation and activity timepoint on mechanical and computational outcomes ($p \leq 0.05$). Proportional Bland-Altman analyses evaluated agreement of maximum FE outcomes during walking in inhomogeneous bone models, which served as the reference standard.

RESULTS: Although rigid bone models produced the highest contact pressures during walking (Figure 1B), material representation, timepoint, and their interaction were not significant (all $p > 0.05$). In contrast, squatting showed significant effects of material representation, timepoint, and interaction (all $p < 0.05$, Figure 1C). At deep flexion, rigid (15.93 ± 5.60 MPa) and one-material (14.82 ± 5.08 MPa) models generated significantly higher pressures than inhomogeneous (11.50 ± 3.05 MPa) and two-material (11.68 ± 3.18 MPa) models (all $p < 0.05$). Maximum shear stress showed no significant effects during either activity (all $p > 0.05$). Maximum strain differed between all phases of walking and squatting (all $p < 0.05$) but there was no effect of material representation ($p > 0.05$). Contact area was not affected by material representation, timepoint, or their interaction (all $p > 0.05$). Bland-Altman analyses revealed significant proportional bias for rigid and one-material models during both activities ($p < 0.05$), whereas the two-material model showed no bias ($p > 0.05$). For shear stress, bias was present only in squatting ($p < 0.05$), while no significant bias occurred for strain. Rigid models required significantly less computing time and memory ($p < 0.05$, Figure 1D, E).

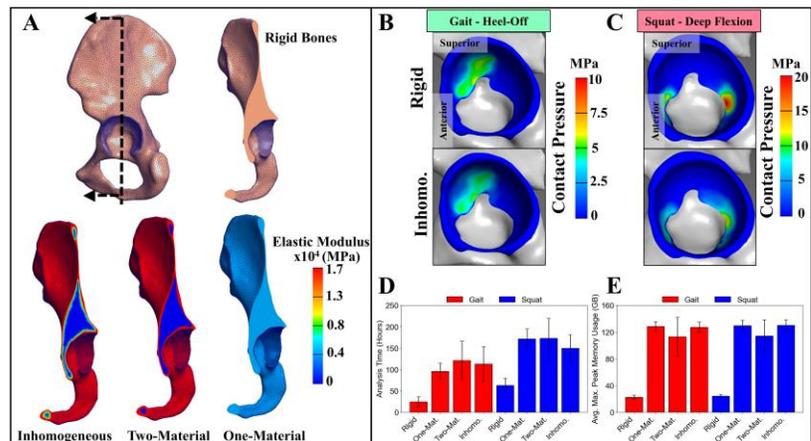


Figure 1: A) Four bone material representations were used to evaluate the effect of bone deformation on chondrolabral mechanics. B) There was no significant effect of material representation on max. contact pressure during level walking; C) during the squat, there was a significant effect of material representation on the max. contact pressure. D) Rigid models required significantly less analysis time and E) maximum memory during simulations of both activities.

DISCUSSION: Although bone material representation did not significantly affect first principal strain, maximum shear stress, or contact area during either level walking or squatting, Bland-Altman analyses revealed that rigid models consistently overestimated contact pressure, with a significant effect for squatting. These activity-specific differences can be explained by joint loading mechanics: during walking, anterior-superior joint reaction forces align with anterior acetabular rotation, facilitating displacement that reduces contact pressure and yields close agreement across models. During squatting, medially directed forces at high flexion angles create posterior acetabular rotation misaligned with the load vector, limiting pressure reduction and amplifying differences between material representations. Despite this divergence, rigid bone models were markedly more efficient, requiring substantially less memory and computing time. The smaller discrepancies in contact pressure compared to prior studies likely reflect differences in model construction and boundary conditions. Collectively, these findings support the use of simplified bone representations when computational efficiency is a priority, though caution is warranted when interpreting contact pressure outcomes—particularly during squatting.

SIGNIFICANCE/CLINICAL RELEVANCE: This research contextualizes the use of the rigid bone assumption with new advancements in finite element modeling, motion capture, and musculoskeletal modeling. Our results provide guidelines for the use of material models for bone that increase modeling efficiency and computation time in large-scale biomechanical analyses.

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