

Evaluation of a Simplified Modeling Approach to Predict Strain in the Cartilage and Labrum of the Hip with Application to Femoroacetabular Impingement Syndrome

Luke T. Hudson^{1,2}, Lindsay L. Schuring^{1,2}, Brooklyn L. Vargas¹, Jeffrey A. Weiss^{1,2,3}, Andrew E. Anderson^{1,2,3}

¹Department of Biomedical Engineering, University of Utah, Salt Lake City, UT, ²Scientific Computing and Imaging Institute, Salt Lake City, UT, ³Department of Orthopaedics, University of Utah, Salt Lake City, UT

luke.hudson@utah.edu

Disclosures: Luke T. Hudson (N), Lindsay L. Schuring (N), Brooklyn L. Vargas (N), Jeffrey A. Weiss (N), Andrew E. Anderson (N)

INTRODUCTION: Femoroacetabular impingement syndrome (FAIS) places individuals at elevated risk of chondrolabral damage, which can progress to hip osteoarthritis (OA). Excessive mechanical strain has been implicated in initiating collagen fibril disruption within articular cartilage, underscoring the importance of accurate strain assessment¹. Patient-specific finite element (FE) models provide a powerful tool to evaluate cartilage and labral mechanics, with prior studies showing strong agreement between FE predictions and experimental data². Despite their accuracy, FE models require substantial expertise, model building, debugging, and computational resources, affecting their practicality for studies involving large patient cohorts. To address these limitations, soft tissue overlap (STO) modeling has emerged as a computationally efficient alternative for estimating strain in the hip. STO models capture subject-specific anatomy and approximate joint contact mechanics by quantifying the geometric overlap of articulating surfaces during kinematically driven activities³. While this method offers simplicity and scalability, its predictive accuracy compared to gold-standard FE models has not been fully established under identical anatomical and boundary conditions. Therefore, the objective of this study was to evaluate the performance of STO models against FE models in predicting cartilage and labral strains in both cam-type FAIS patients and controls with radiographically normal hip morphology.

METHODS: Six patients with FAIS (N=4M/2F, age: 28.0 ± 6.7 years, weight: 74.5 ± 9.9 kg) and eight controls (N=4M/4F, age: 23.6 ± 2.2 years, weight: 64.7 ± 11.5 kg) were selected from a prior cohort⁴. Patient-specific FE meshes and STO surface models were generated from segmented CT arthrography images of the acetabular labrum, cartilage, pelvis, and proximal femur. For FE models, acetabular and femoral cartilage were modeled as anisotropic hyperelastic with depth-dependent collagen fiber orientation, while the labrum was represented as transversely isotropic hyperelastic with circumferential fibers⁵. The pelvis and femur were modeled as rigid. STO models treated all structures as rigid surfaces. FE models were analyzed with FEBio (www.febio.org), driven by subject-specific kinematics from biplane radiography and individualized hip joint contact forces estimated by an OpenSim musculoskeletal model. The observed FE kinematics were applied to STO models to ensure identical boundary conditions. STO strains were estimated from overlap distances between femoral cartilage and acetabular cartilage/labrum, while FE strains were calculated by projecting the right stretch tensor along the unit normal of each face. FE-predicted normal compressive strains at each face were compared directly to STO predictions. Agreement between FE and STO strains was assessed at heel-strike (HS), foot flat (FF), midstance (MS), and heel-off (HO) during level walking using a repeated-measures Bland-Altman analysis. Limits of agreement were derived from a mixed-effects model, with subject and mesh face as random effects and gait event as the fixed effect⁶.

RESULTS: Across the gait cycle, median (IQR) cartilage strains predicted by the FE model were 0.057 (0.059) in the FAIS group and 0.060 (0.053) in the control group, compared with STO model medians of 0.046 (0.045) and 0.049 (0.042), respectively. Bland-Altman analysis demonstrated a mean bias of -0.008 [95% CI -0.017 to -0.002] for the cartilage in the FAIS group and -0.011 [-0.018 to -0.005] for the cartilage in the control group (Fig. 1A). Proportional bias slopes were 0.33 and 0.37, with 95% limits of agreement ranging from approximately -0.015 to $+0.035$ across both cohorts. For the labrum, STO strains were higher than FE, with FE medians (IQR) of 0.018 (0.011) in FAIS group and 0.018 (0.013) in the control group compared to STO medians of 0.050 (0.049) and 0.060 (0.057) (Fig. 2B). Mean bias values were effectively zero [-0.033 to 0.026] for FAIS group and 0.003 [-0.027 to 0.025] for the control group. Proportional bias slopes were -0.93 and -1.01 , and limits of agreement were narrower and negative, ranging from about -0.043 to -0.015 . Qualitative comparisons of strain patterns between models demonstrated good agreement for moderate cartilage strains and small labral strains across all phases of walking (Fig. 2A). However, STO models consistently overpredicted labral strains when considerable labral deflection occurred due to impingement (Fig. 2B). FE models consistently predicted uniform strain patterns across cartilage and labrum, while STO models were less consistent, predicting smaller areas of strain across the chondrolabral interface.

DISCUSSION: Cartilage strains predicted by FE and STO models were generally comparable across the gait cycle for small to moderate compressive strains. Small negative biases indicated that STO predicted slightly higher cartilage strains than FE modeling overall, with most individual differences falling within ± 0.03 strain units. However, proportional biases showed that disagreement increased with strain magnitude, as STO predicted lower strains than FE modeling at greater cartilage strain levels. In contrast, larger discrepancies were observed for the labrum. Although mean bias values were near zero, STO labral strains were roughly three times higher than FE values. Strongly negative proportional biases indicated that with increasing strain magnitude, STO predictions consistently overestimated FE predictions. The narrower, uniformly negative limits of agreement highlighted this systematic underestimation, particularly in regions of elevated labral strain. This trend aligns with previous findings where STO models overestimated labral strain during daily activities³. These differences likely arise from the ability of FE modeling to capture labral deflection due to contact with the femur, which is not captured in STO modeling. Consequently, STO tended to overpredict labral strain and underpredict cartilage strain during level walking. Nonetheless, STO models reliably identified regions of highest cartilage and labral strain, indicating potential impingement.

SIGNIFICANCE/CLINICAL RELEVANCE: These findings highlight the potential of STO models as a scalable tool for detecting regions of elevated cartilage and labral strain associated with FAIS, offering a pathway toward clinically relevant assessments in larger patient cohorts. By capturing key patterns of impingement, STO models may help bridge advanced biomechanical modeling with practical clinical applications.

REFERENCES: 1. Occhetta, P., Nat Biomed Eng. 2019. 2. Anderson, A.E., J Biomech Eng, 2008. 3. Schuring, L.L., J Biomech, 2023. 4. Atkins, P.R., J Orthop Res, 2020. 5. Todd, J.N., Clin Orthop Relat Res, 2022. 6. Bland, J.M., J Biopharm Stat, 2007.

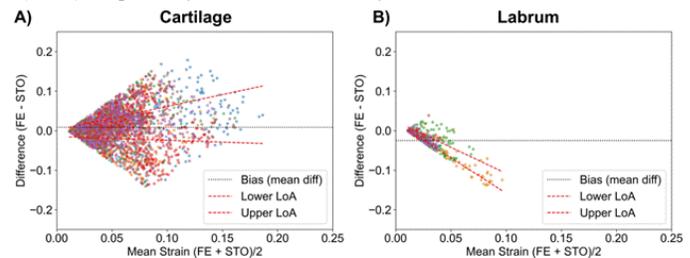


Figure 1: (A) Bland-Altman analysis of cartilage and (B) labrum in FAIS group showed close agreement between STO and FE models for low to moderate strain levels during walking. With increasing labral strain, bias (FE - STO) became progressively more negative, reflecting systematic overestimation of strain by STO models. Negative bias indicates STO overestimation, while positive bias reflects STO underestimation. Red dashed lines denote limits of agreement, black dotted line indicates overall bias.

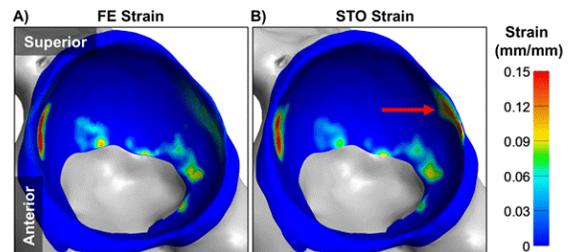


Figure 2: STO models overpredicted labral strain in areas of significant labral deformation during level walking. Red arrow indicates area of higher labral strain predicted by the STO model.