Proposed Symptom-Avoidance Strategies in Femoroacetabular Impingement Syndrome Identified Through 3D Shape-Kinematic Correlates

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INTRODUCTION: Cam morphology is common amongst young adults with femoroacetabular impingement syndrome (FAIS) and is frequently observed in patients with end-stage hip osteoarthritis (OA). However, ~35% of the general population exhibits cam morphology without a history of hip pain or radiographic evidence of OA [1], suggesting morphology alone is not solely responsible for abnormal hip joint biomechanics and symptomatic impingement. Results from the few prior biomechanical studies that have included controls with cam deformities suggest that reduced sagittal plane spinopelvic mobility contributes to the presence of symptoms [2]. Traditional techniques for measuring hip morphology and kinematics are error prone due to 2D representation of complex 3D shapes and the hip's deep anatomical location. Unfortunately, error-prone measurement techniques hinder the detection of subtle shape-motion relationships that could differentiate motion differences driven by symptoms from those driven by morphology. Fortunately, combing statistical shape modeling (SSM) with model-based tracking of biplane fluoroscopy (BF) provides objective characterization of 3D hip morphology and accurate quantification of in vivo hip motion. Herein, we identified specific shape-motion relationships underlying symptom-inducing versus symptom-avoidant compensation strategies through correlation of SSM and BF data.

METHODS: Symptomatic patients with cam FAIS and asymptomatic individuals with (positive controls) and without (negative controls) cam morphology were recruited under IRB approval (**Table 1**). Two orthopedic surgeons identified cam morphology from x-ray or MRI. CT or MRI data were segmented to reconstruct 3D femur and pelvis surfaces. All participants were imaged with BF while standing and treadmill walking at a self-selected speed. Femur and pelvis surfaces were used to create two particle-based correspondence SSMs (ShapeWorks) to quantify morphological variation of the cohort (femur: 2048 particles, pelvis: 4096 particles). Principal component analysis (PCA) was used to reduce the dimensionality of SSM results and group PC score contributions to PCA modes were compared. Femur and pelvis surfaces were also used to measure hip and pelvis orientation from BF data across the gait cycle in 3D [3]. Kinematics were analyzed with and without correction for neutral standing posture to assess motion and orientation differences, respectively. Kinematic differences between groups were evaluated across the gait cycle and at timepoints of approximate push-off (PO) and heel-strike (HS). One-way ANOVAs with Dunn-Sidak correction ($\alpha=0.05$) were used for all groupwise comparisons. Lastly, linear regression was performed between groupwise significant PCA mode scores and discrete raw kinematic metrics across the population and within groups to assess the relationship between shape and orientation.

RESULTS: Femurs of FAIS patients displayed features consistent with a more prominent cam region and greater neck-shaft angle, which were described by a groupwise greater contribution to femur PCA mode 4 compared to negative controls (**Figure 1**). Patients were also oriented in greater hip external rotation at PO (3.61 ± 5.78°) and had relatively less posterior pelvic tilt at HS (-0.57 ± 3.25°) than negative controls (hip ext. rotation: -2.03 ± 4.59°, p=0.02; pelvic tilt: -3.39 ± 2.73°, p=0.04), but not positive controls (hip ext. rotation: 2.92 ± 5.72°; pelvic tilt: -0.39 ± 2.86°). Femur mode 4 was negatively correlated with hip flexion at HS across the cohort and strongly correlated with pelvic axial internal rotation in positive controls at PO (**Figure 1**).

DISCUSSION: Herein, we observed that FAIS patients displayed altered gait kinematics, and femoral features characteristic of patients were associated with reduced hip flexion across the cohort and greater pelvic internal rotation among positive controls. Our results align with previous work identifying increased hip external rotation [3] and altered sagittal pelvic mobility in patients [2]. Our results also suggest a novel FAI symptom-avoidance strategy involving pelvic internal rotation mobility at PO, where hip joint contact forces are directed anterosuperiorly [4] coinciding with where cartilage damage is most prevalent in FAIS patients [5]. Positive controls with femurs most like patients may avoid damage in the anterosuperior region of the cartilage by utilizing pelvis internal rotation to accommodate cam morphology as opposed to relying primarily on femoral external rotation like patients.

SIGNIFICANCE/CLINICAL RELEVANCE: This study underscores pelvic mobility – in all planes – as a potential intervention target and lays the groundwork for phenotyping FAIS symptomatology to enable more patient-specific treatment strategies.

REFERENCES: [1] Frank JM (2015). *Arthroscopy*, **31**. [2] Pierannunzii L (2017). *J Orthop Traumatol*, **18**: 187-96. [3] Atkins PR (2020). *J Orthop Res*, **38**: 823-33. [4] Ng KCG (2018). *Am J Sports Med*, **46**: 2615-23. [5] Beck M (2005). *J Bone Joint Surg Br*, **87**:1012-18

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IMAGES AND TABLES:

Table 1: Population demographics. BMI in kg/m^2

	Side	Sex	Age	BMI
Patient (n=23)	16 R / 7 L	12 M / 11 F	28 ± 6.9*	24.5 ± 3.3*
Pos ctrl (n=14)	11 R / 3 L	8 M / 6 F	27 ± 4.8*	23.2 ± 2.1*
Neg ctrl (n=11)	6 R / 5 L	6 M / 5 F	23 ± 2.2	21.0 ± 2.0

*Significantly different from negative controls

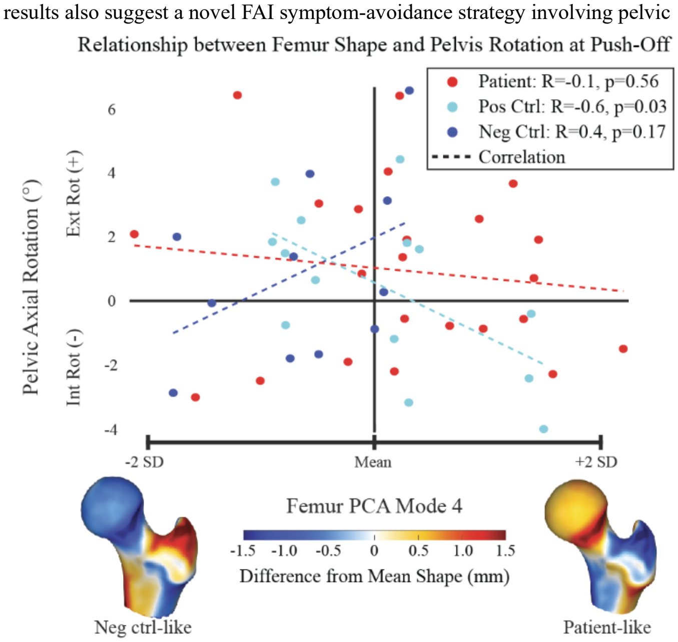

Figure 1: Positive controls with more patient-like femurs displayed a more internally rotated pelvis at push-off, as indicated by a strong correlation between PC score and internal pelvis rotation. Regression lines (top) highlight a stronger correlation for positive controls than patients. Shape variation along ±2 SD of femur PCA Mode 4 (bottom) depicts features that significantly differ between patients and negative controls ($p<0.05$). Red and blue in colormaps indicate regions where bone is more or less prominent compared to the population mean femur shape, respectively.