Application of Statistical Shape Modeling to Predict Clinical Metrics of Femoral Head Coverage in Patients with Developmental Dysplasia
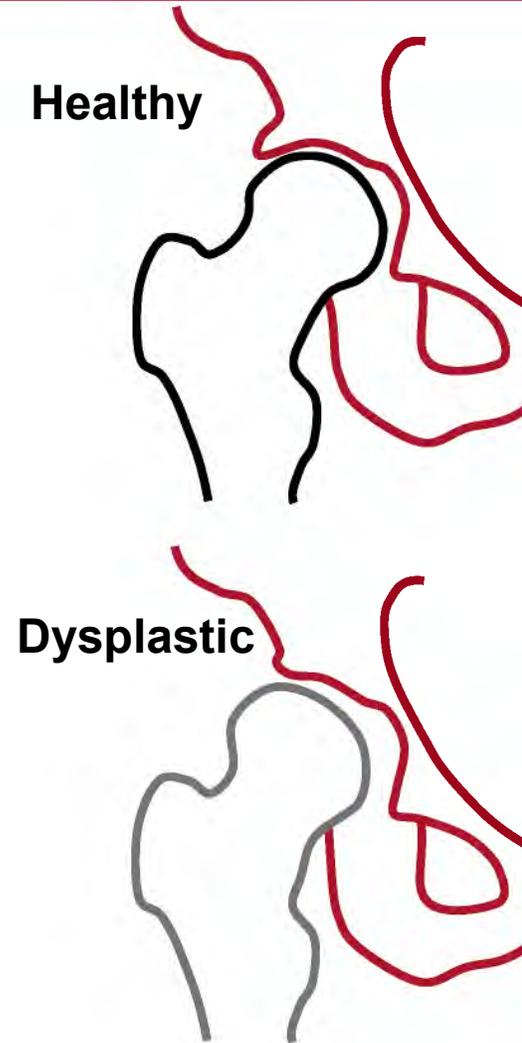
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Motivation

- Hip dysplasia is characterized by undercoverage of the femoral head

  - Mechanical instability, cartilage degeneration, pain

- Surgical rotation of the acetabulum aims to increase coverage

  - Inadequate or over- correction results in residual symptoms[2,3]

Healthy

Dysplastic

[1] Lerch TD et al. *Clin Orthop Relat Res*, 2017; 475(4):1154-1168. [2] Albers CE et al. *Clin Orthop Relat Res*, 2013; 471(5):1602-1614.

Problem Statement

- Pre-operative characterization of joint coverage often relies on 2D measurements from radiographs
  - Utilize sphere fitting and are limited to single projection
  - Do not accurately predict 3D joint coverage[1]

[1] Nepple JJ et al. *Clin Orthop Relat Res.*, 2017; 475(4):1037-1044.
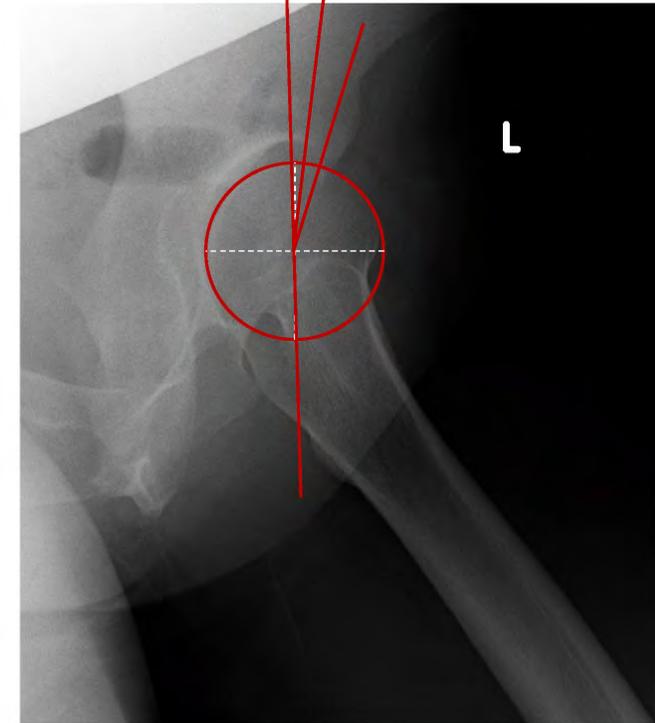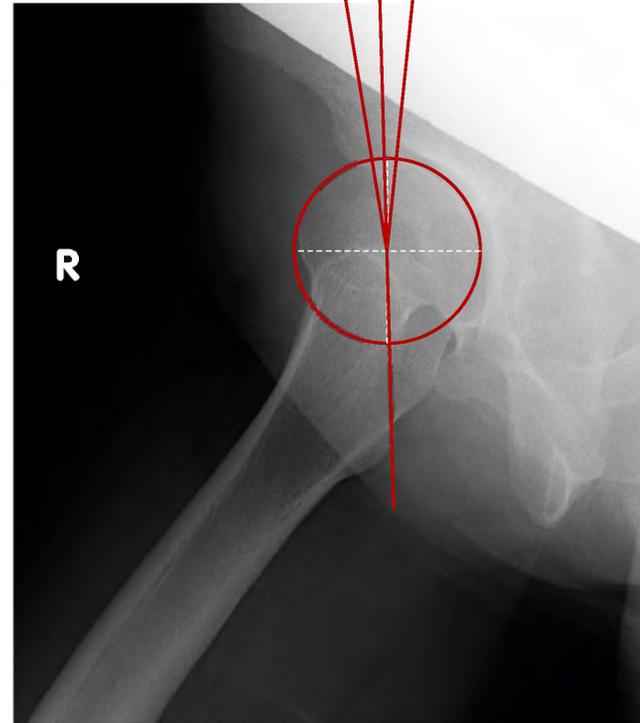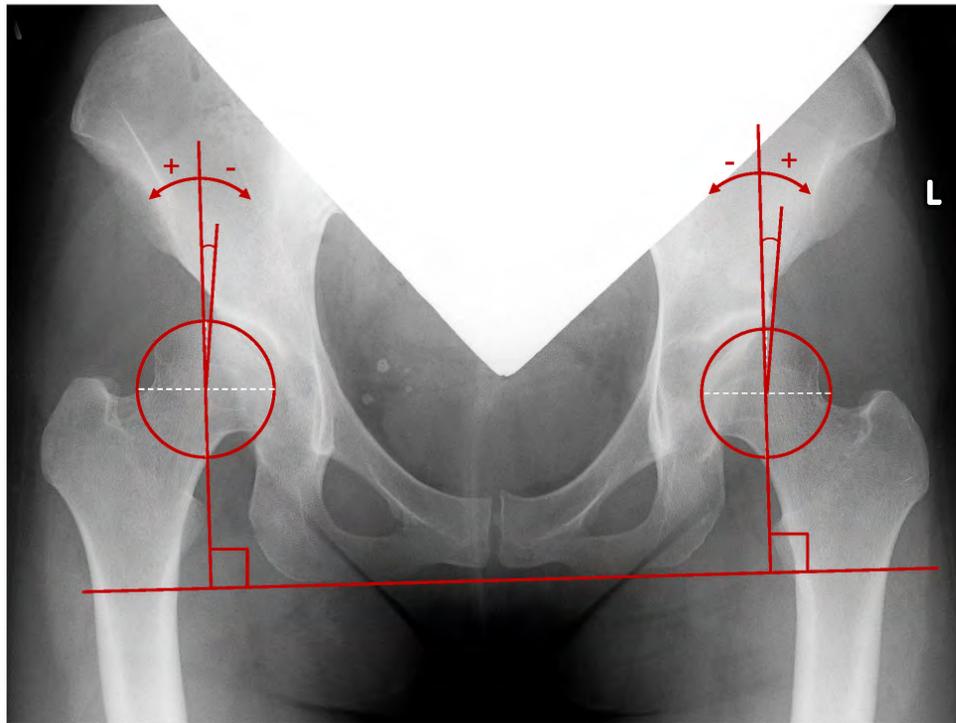
Problem Statement

- Lack of standardization as to how to quantify morphology in 3D

- Statistical shape modeling (SSM) provides an objective measurement of 3D shape
  - Considers the entire structure without manual definition of regions of interest

[1] Nepple JJ et al. *Clin Orthop Relat Res.*, 2017; 475(4):1037-1044.

Objectives

1. Apply a multi-domain, 'articulated' SSM to quantify the pose and shape of the hip in patients with hip dysplasia

2. Determine whether identified pose and shape variations quantified by SSM are predictive of 3D measurements of femoral head coverage
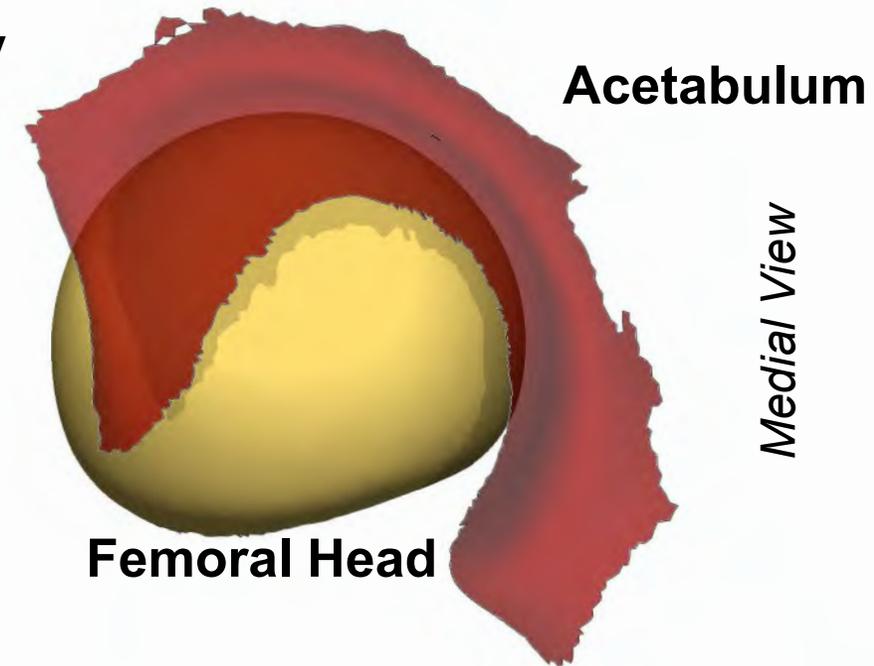
Methods

- Full femur and hemi-pelvis segmented and reconstructed from CT images[1,2]
  - 83 hips from 47 females with hip dysplasia

- Shapes were preprocessed and input to multi-domain SSM
  - Iterative closest point alignment of each bone pair
  - Correspondences optimized for the femur (n=4,096) and pelvis (n=2,048)
  - Correspondences for the femoral head (n=339) and acetabulum (n=119) were isolated

[1] Agrawal P et al. *ShapeMI 2020;* 111-121. [2] Atkins PR et al. *J Orthop Res*, 2021; 1-14.
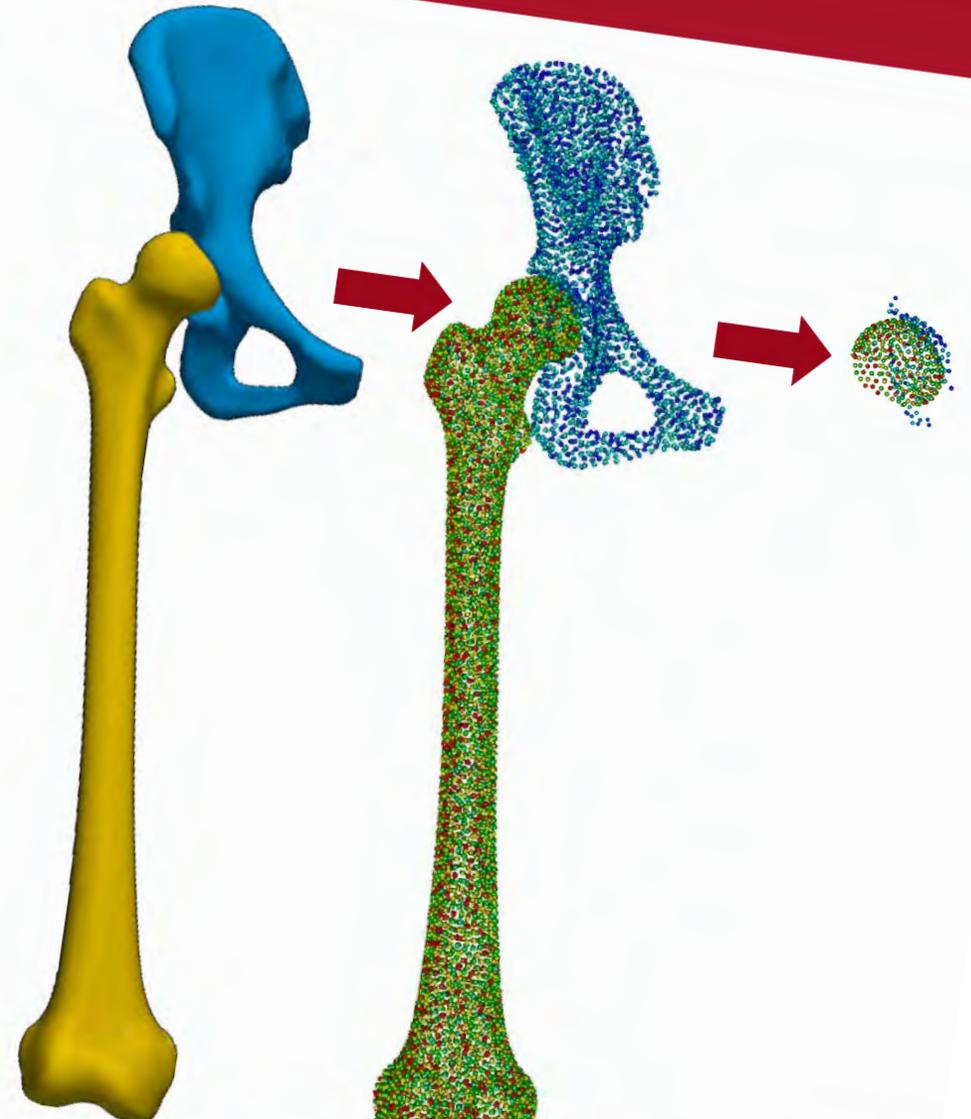
Methods

- Coverage was measured in FEBioStudio[1]
  - Ranged from 27.3% to 39.4%

$$Coverage = \left(\frac{Covered}{Uncovered}\right) \times 100\%$$

- Correspondence particles analyzed to quantify 3D morphology
  - Principle component analysis (PCA)
  - Linear discriminant analysis

- LASSO regression used to isolate the PCA modes predictive of coverage
  - Analysis completed for two datasets:
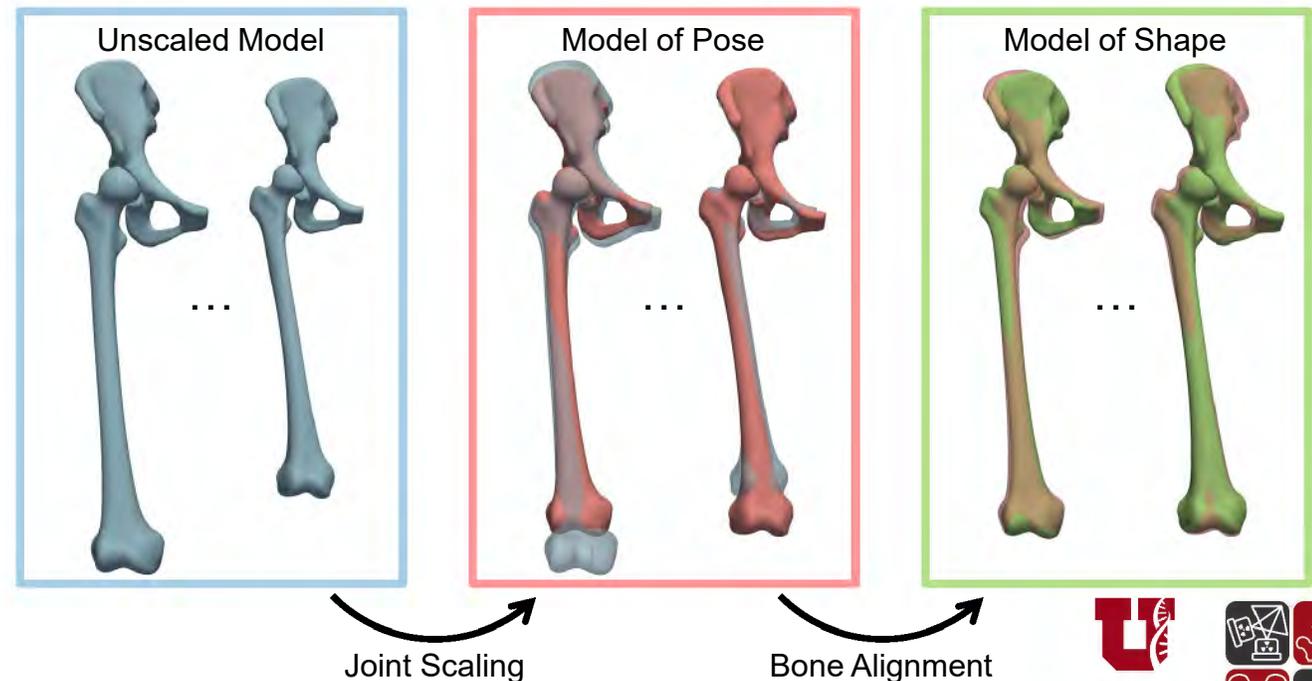   - Full femur and hemi-pelvis
    - Femoral head and acetabulum

Acetabulum

Medial View

Femoral Head

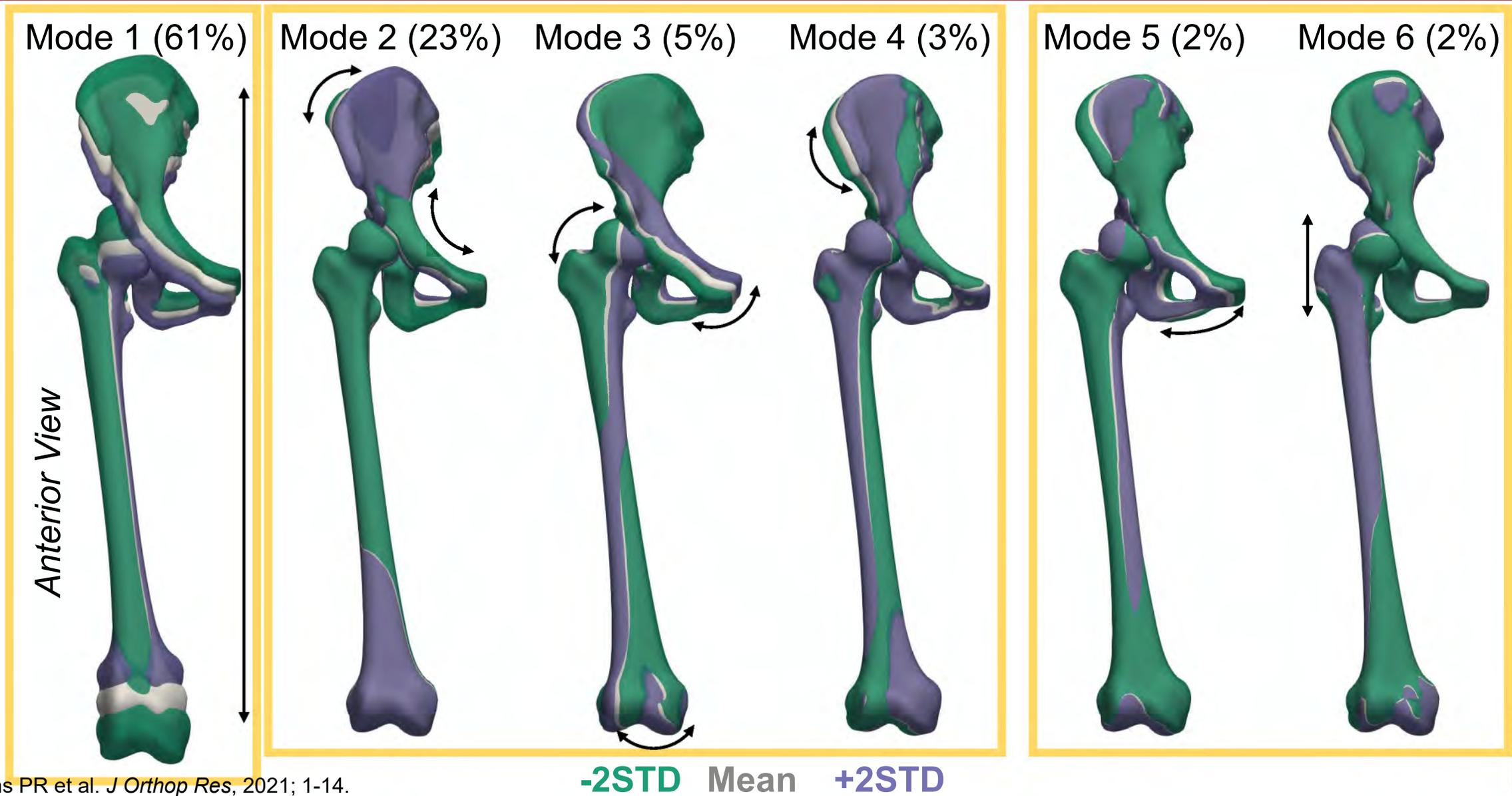[1] *febio.org* [2] Atkins PR et al. *J Orthop Res*, 2021; 1-14.

Statistical Analysis of Articulating Joints

- Traditionally ShapeWorks has been applied to defining anatomical bone or tissue shapes, ignoring:
  - Relationship of shape variation between domains
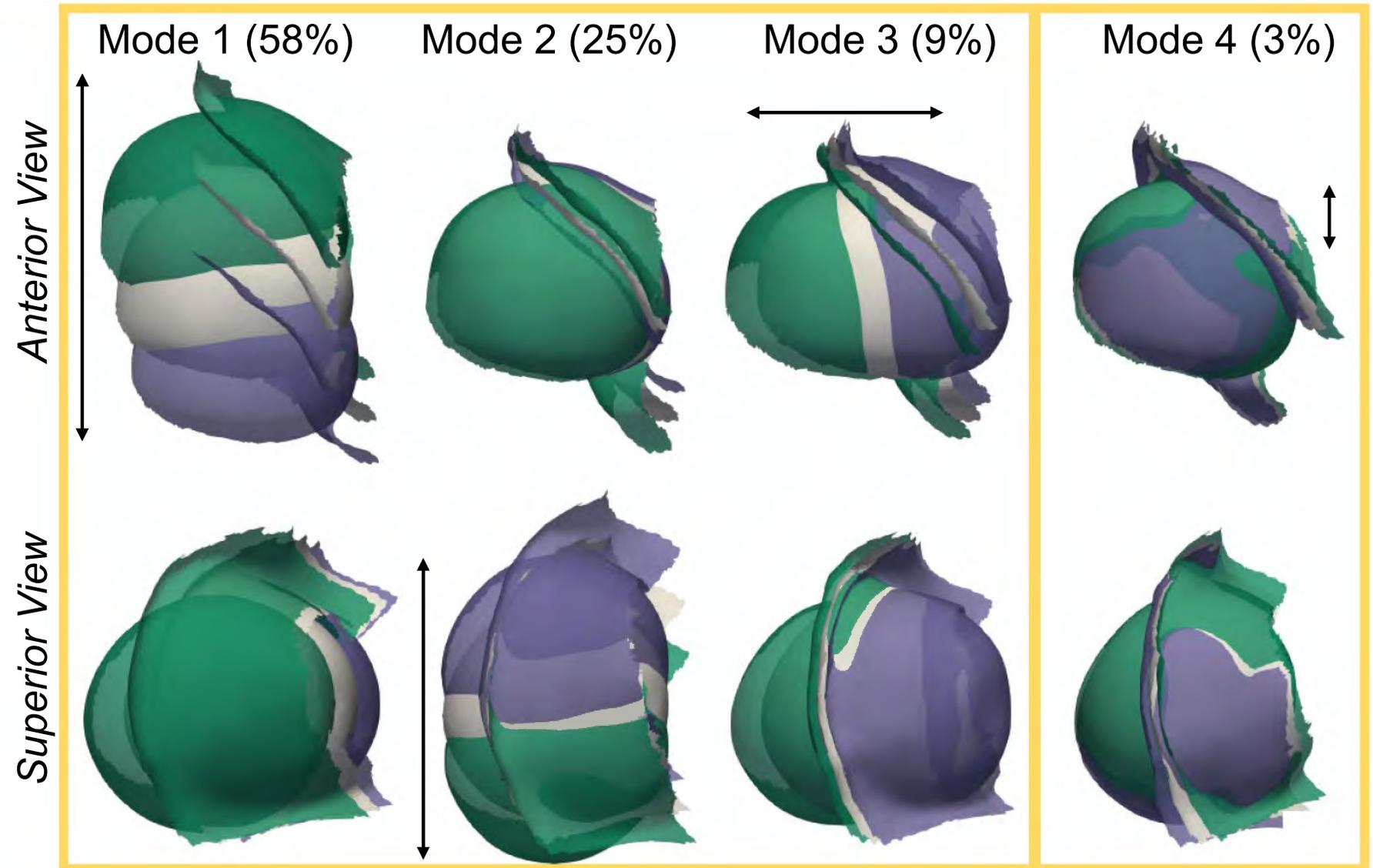 - Positional relationship between multiple domains (i.e. pose)

- Two-step alignment approach[1]
  - Quantify joint pose and shape
  - Evaluate bone shape
    - Joint shape
    - Independent bones

Unscaled Model   Model of Pose   Model of Shape

Joint Scaling   Bone Alignment

[1] Agrawal P et al. ShapeMI, 2020; 111-121. [2] Atkins PR et al. *J Orthop Res*, 2021; 1-14.

PCA Modes of Unscaled Variation (% Total Variation)

Mode 1 (61%)   Mode 2 (23%)   Mode 3 (5%)   Mode 4 (3%)   Mode 5 (2%)   Mode 6 (2%)

Anterior View

-2STD   **Mean**   **+2STD**

[1] Atkins PR et al. *J Orthop Res*, 2021; 1-14.

PCA Modes of Unscaled Variation (% Total Variation)

Mode 1 (58%)   Mode 2 (25%)   Mode 3 (9%)   Mode 4 (3%)

Anterior View

Superior View

-2STD   **Mean**   **+2STD**

[1] Atkins PR et al. *J Orthop Res*, 2021; 1-14.

PCA Modes of Variation in Full Bone Pose and Shape

Mode 1: Flexion-
Extension

Mode 2: Abduction-
Adduction

Mode 4: Internal-
External Rotation

-2 SD   **Mean**   **+2 SD**

PCA Modes of Variation in Full Bone Pose and Shape
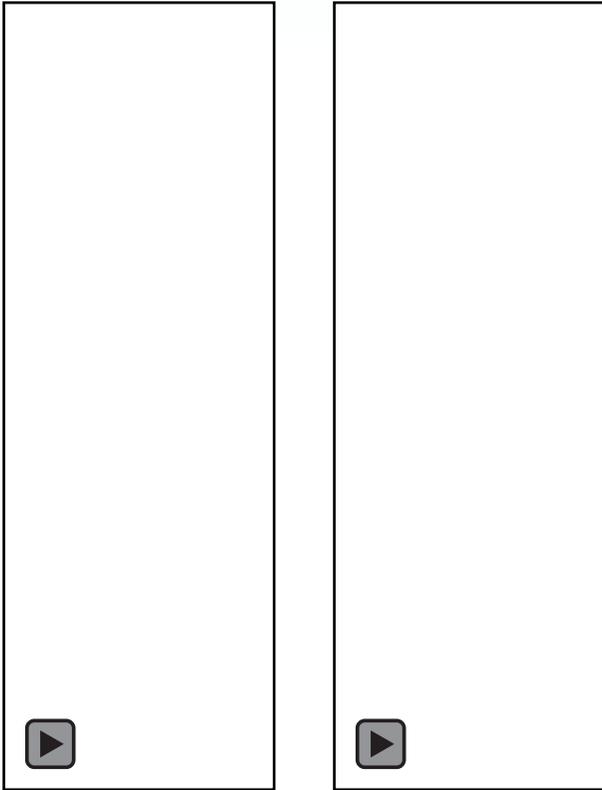
Mode 1: Flexion-
Extension
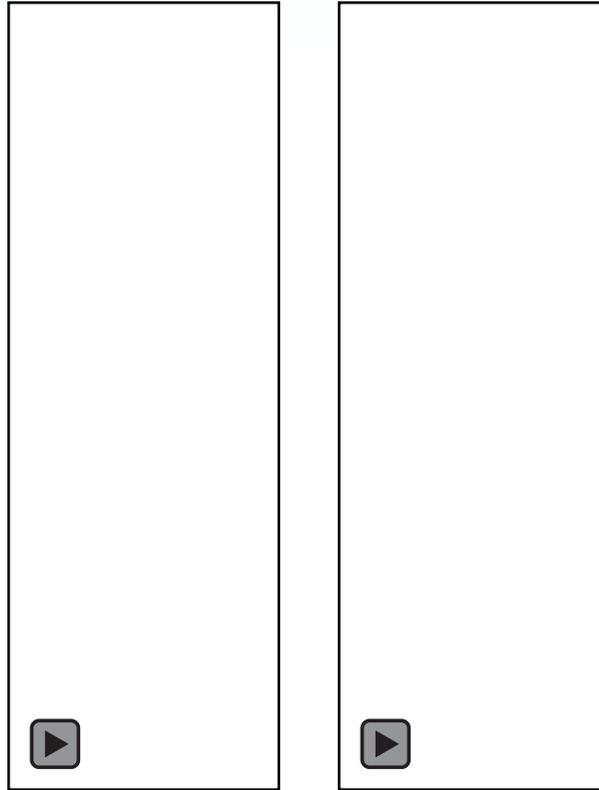
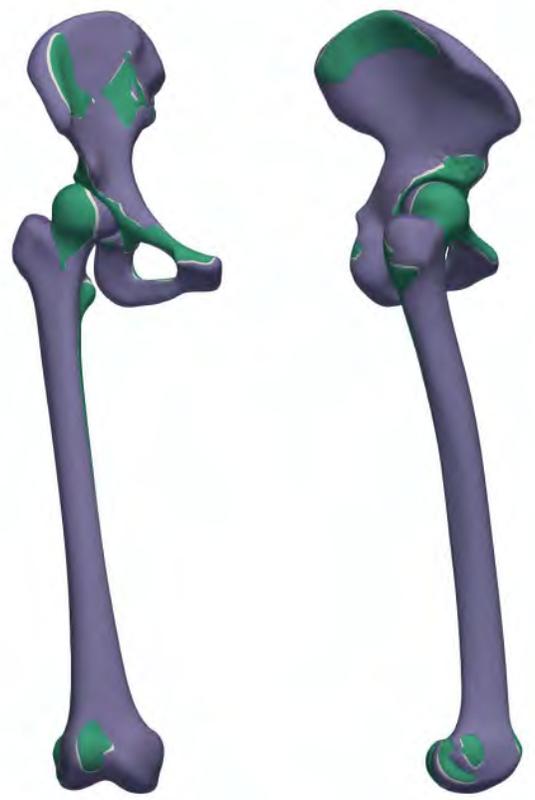Mode 2: Abduction-
Adduction
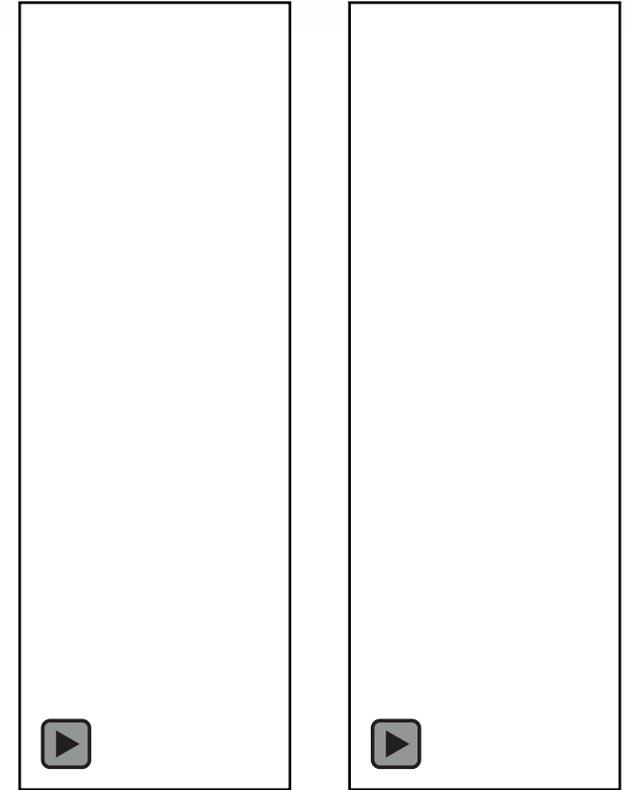
Mode 4: Internal-
External Rotation

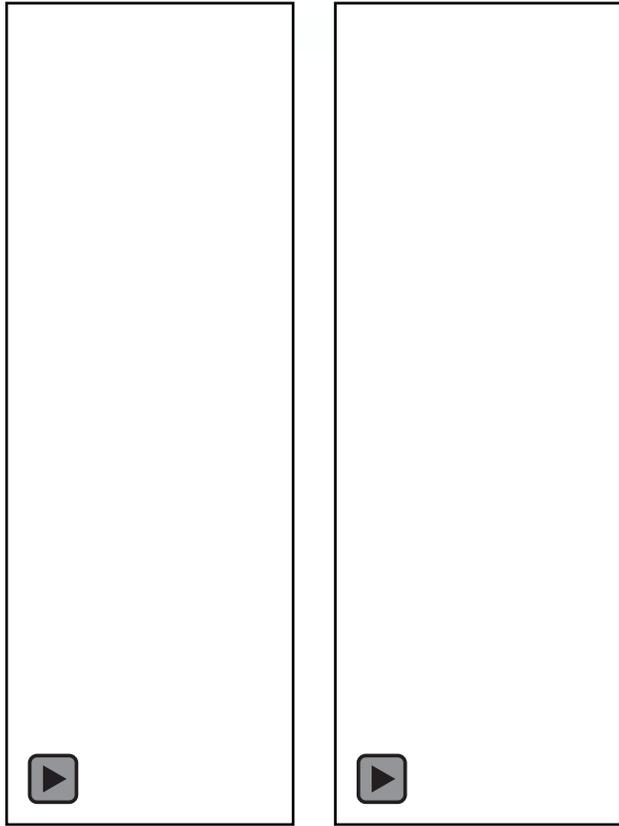# PCA Modes of Variation in Bone Shape
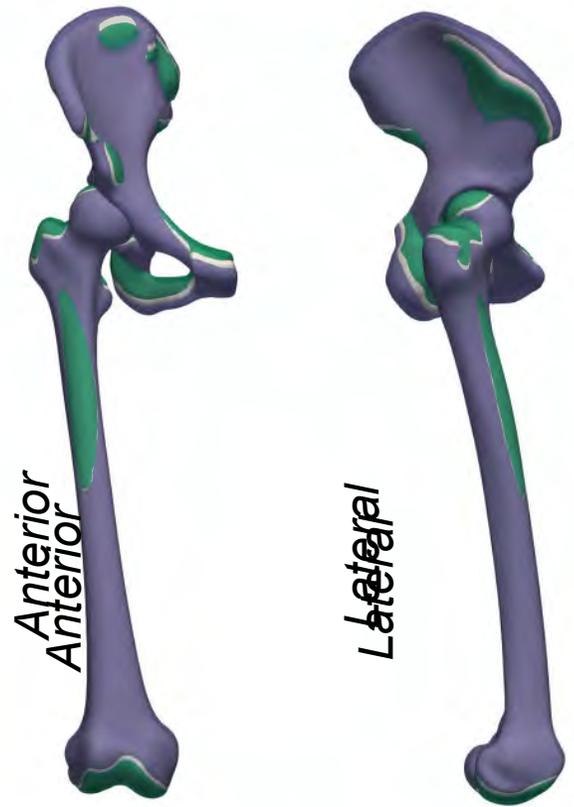
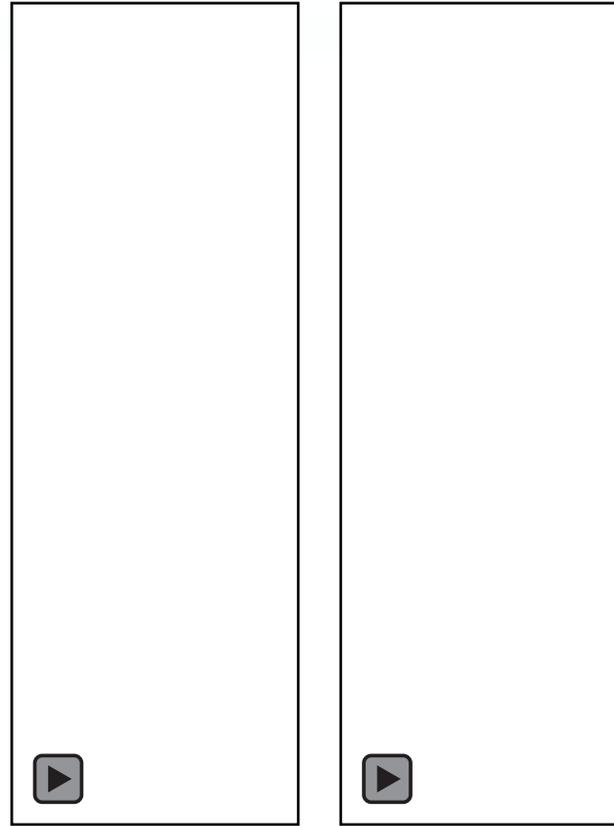Mode 1: Pelvis-Femur
Height

Mode 2: Head and
Pubis Position

Mode 3: Femoral
Version/Bone Thickness
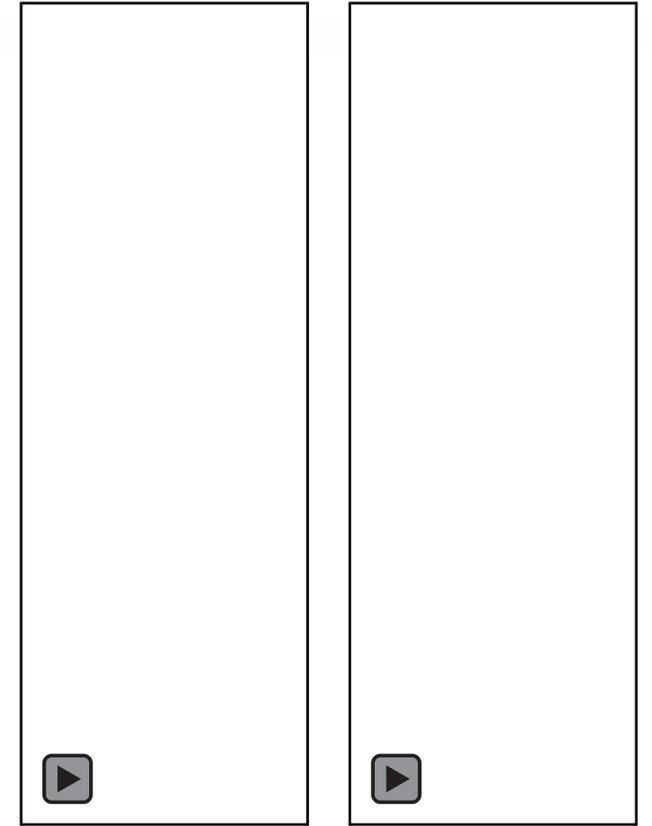
-2 SD   **Mean**   **+2 SD**

PCA Modes of Variation in Bone Shape

Mode 1: Pelvis-Femur
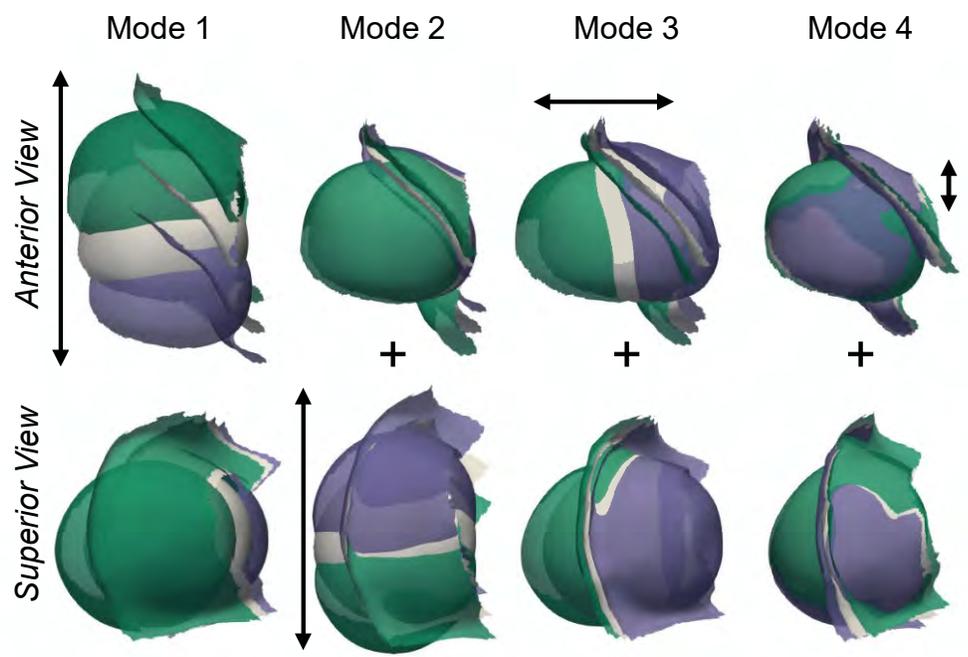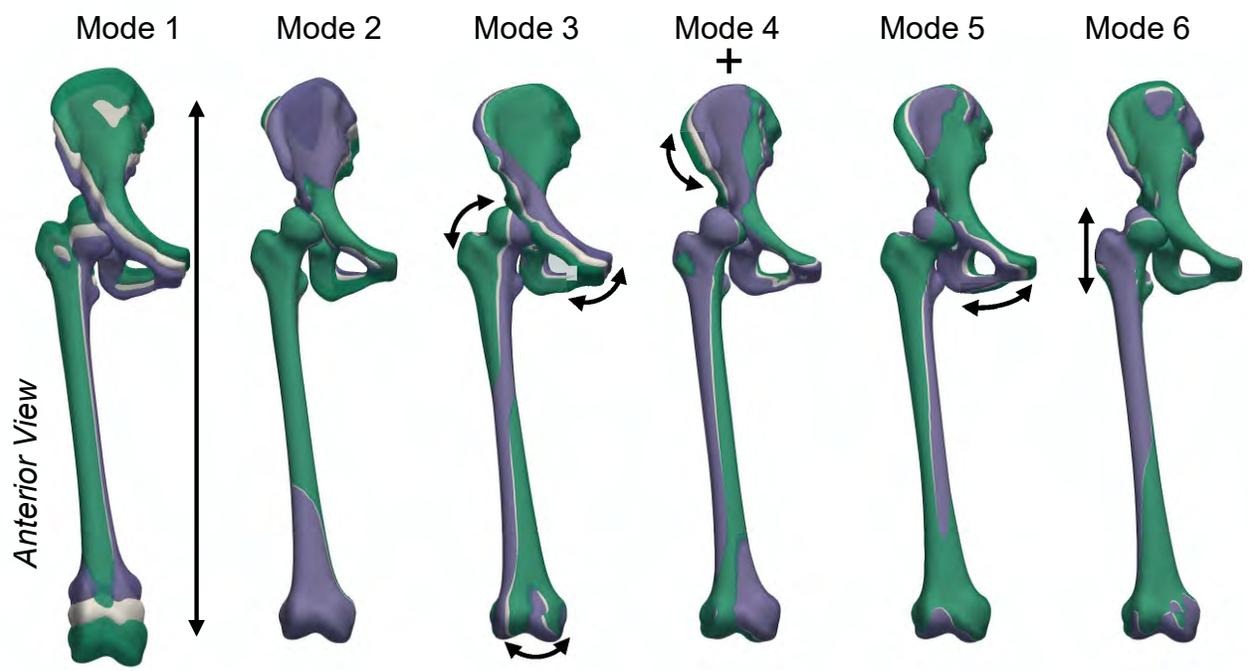Height

Mode 2: Head and
Pubis Position

Mode 3: Femoral
Version/Bone Thickness

Unscaled Model Shape Variation

Full Bone Model

Joint Model

Anterior View

Mode 1   Mode 2   Mode 3   Mode 4   Mode 5   Mode 6

Mode 1   Mode 2   Mode 3   Mode 4

Anterior View
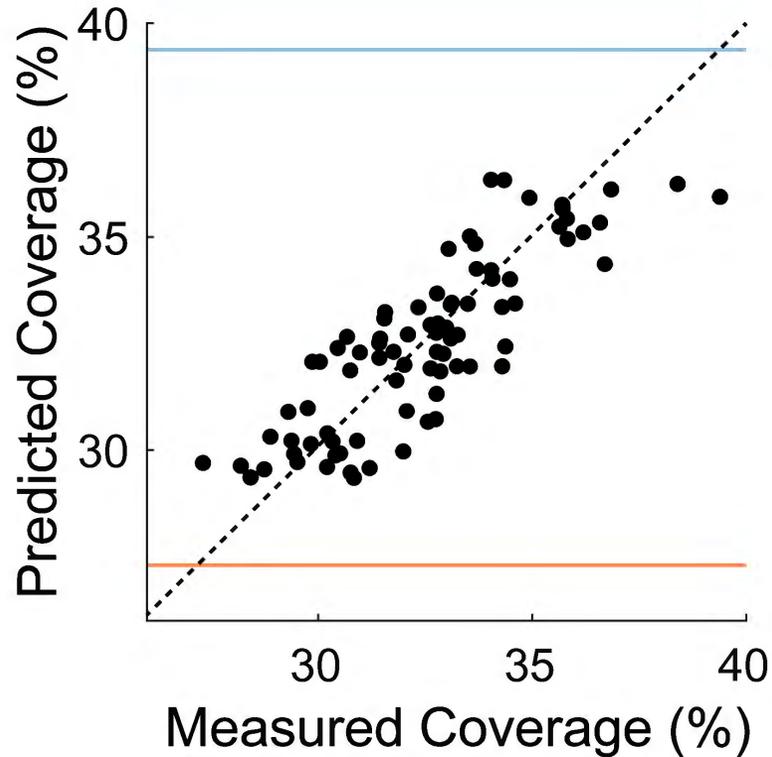
Superior View

-2 SD   Mean   +2 SD

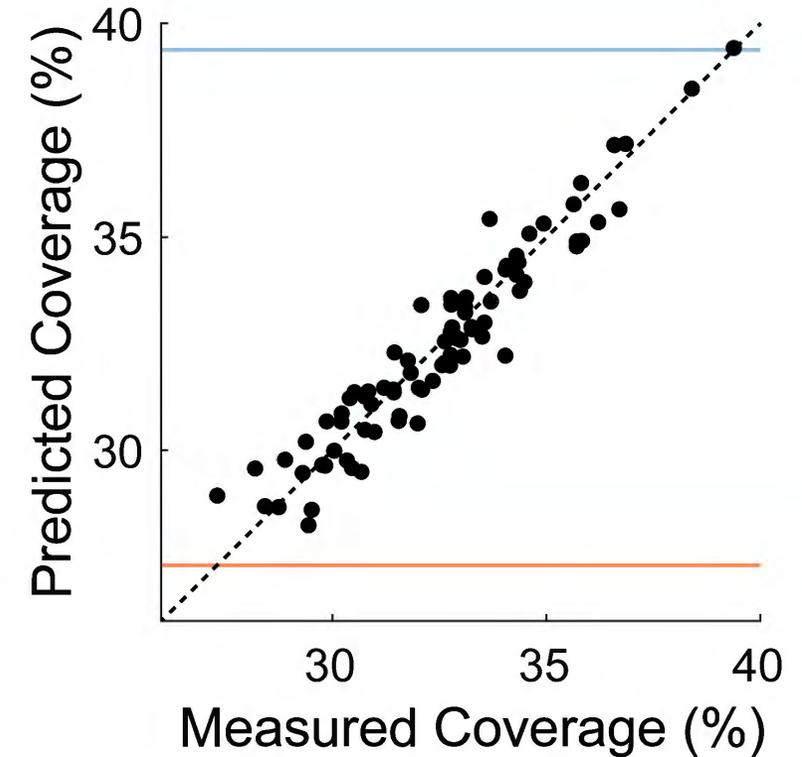# Coverage Regression Analysis: Unscaled Model

Full Bone Model

- 8 PCA modes
  - 6% of the overall variability

- Mean error of 0.9% coverage

Joint Model

- 13 PCA modes
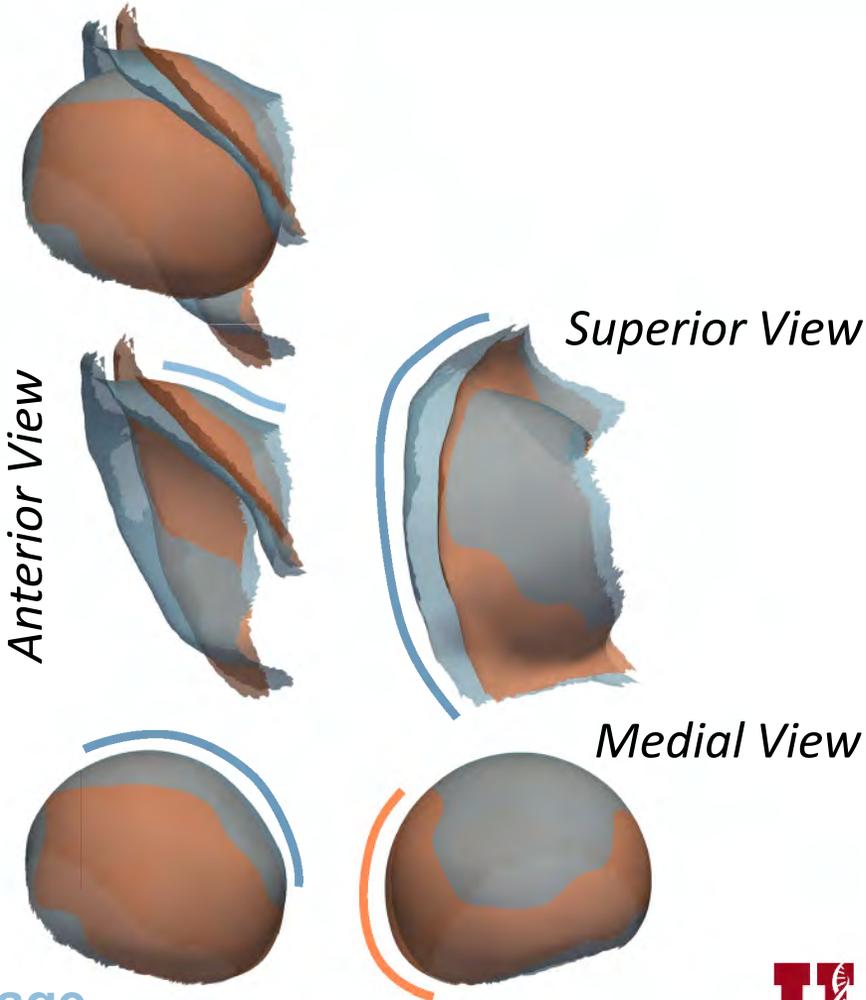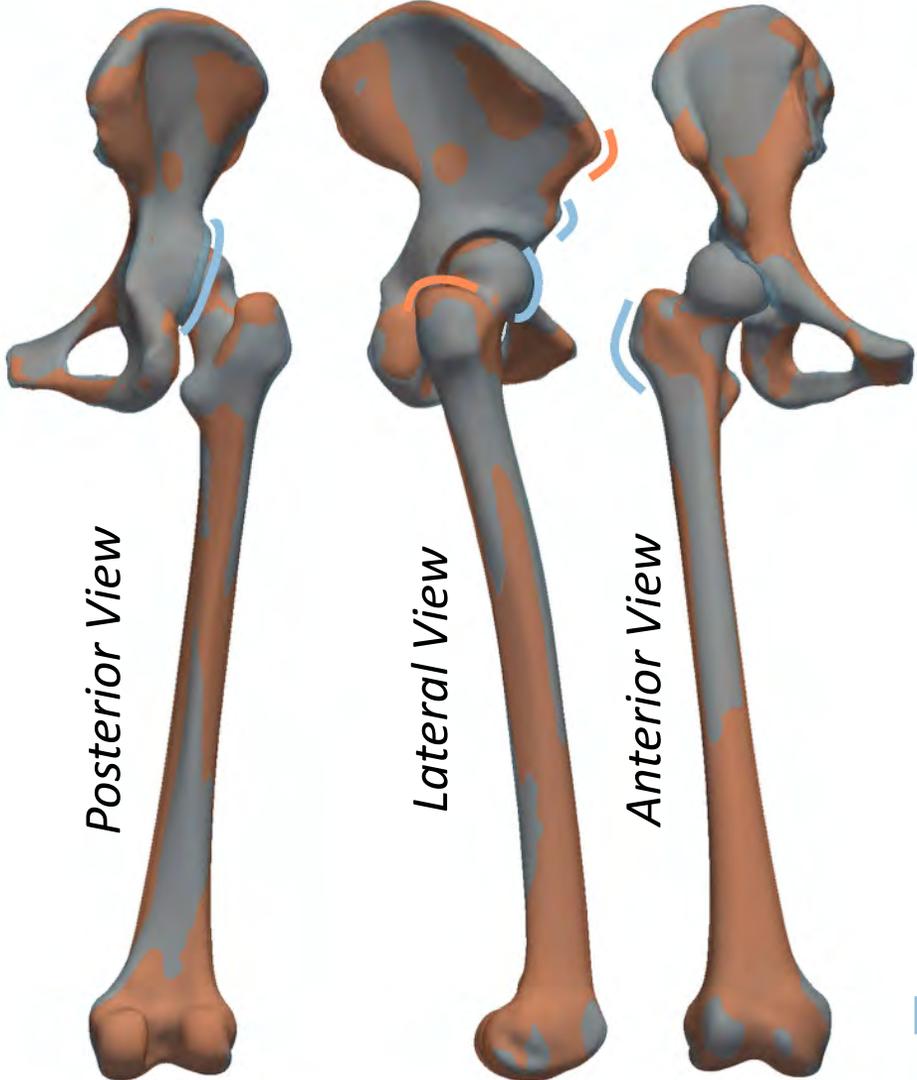 - 40% of the overall variability

- Mean error of 0.6% coverage

Maximum Coverage
Minimum Coverage

[1] Atkins PR et al. *J Orthop Res*, 2021; 1-14.

Linear Discriminant Reconstruction: Coverage

Full Bone Model

Joint Model

Posterior View

Lateral View

Anterior View

Anterior View

Superior View

Medial View

Maximum Coverage
Minimum Coverage

[1] Atkins PR et al. *J Orthop Res*, 2021; 1-14.

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Conclusions

- Observed pose and shape related variation in the significant modes of variation from our multi-domain SSM of the hip joint of patients with hip dysplasia

- Coverage was predicted by shape variation commonly associated with hip dysplasia

- Morphology over muscle attachment sites may contribute to coverage
  - Indicative of functional adaptations

Contact penny.atkins@utah.edu for additional information.

Join us for our ShapeWorks Workshop tomorrow at 10:45!

Data provided by Dr. Tokunaga, Nara Institute of Science and Technology.

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