Combination of Statistical Shape Modeling and Statistical Parametric Mapping to Quantify Cartilage Contact Mechanics in Hip Dysplasia

Penny R. Atkins, Shireen Y. Elhabian, Jeffrey A. Weiss, Ross T. Whitaker, Christopher L. Peters, Andrew E. Anderson

University of Utah Scientific Computing and Imaging Institute and the Departments of Orthopaedics, Computer Science, Biomedical Engineering, and Physical Therapy

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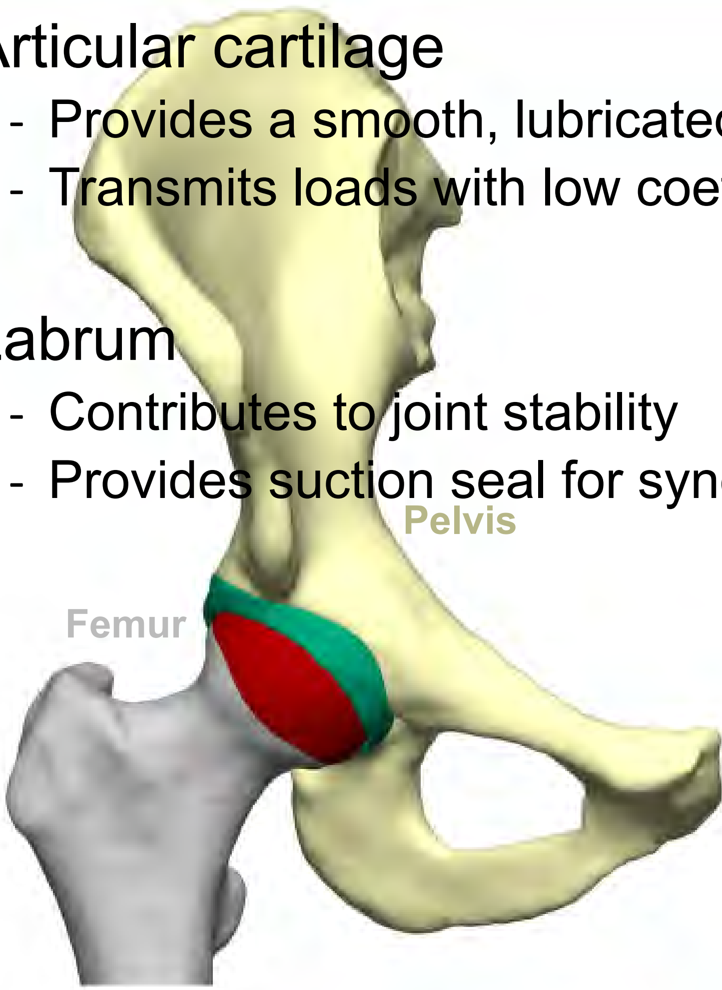
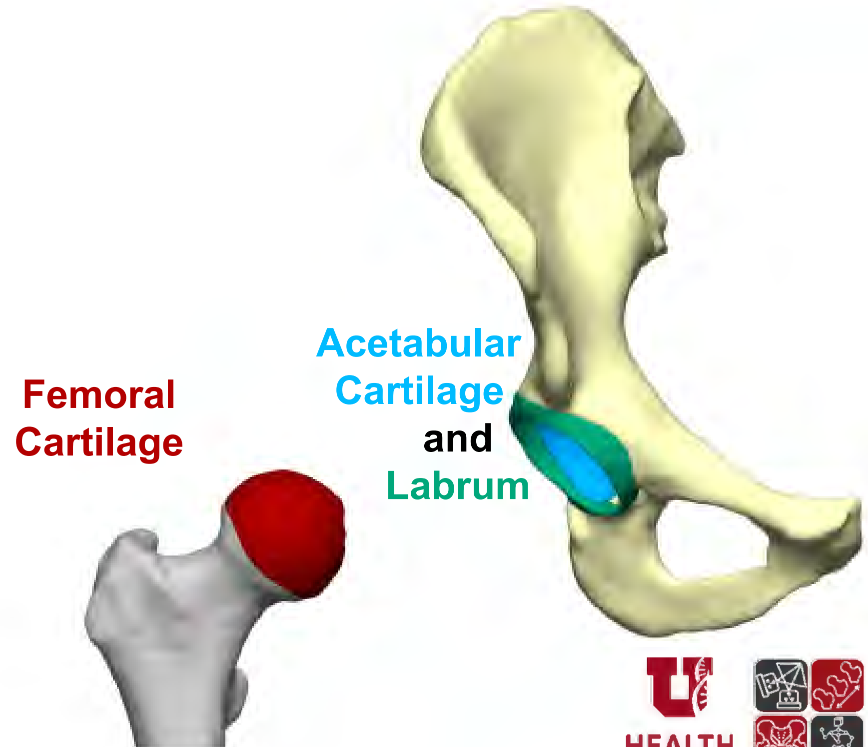
Anatomy of the Hip

- Articular cartilage
  - Provides a smooth, lubricated surface for articulation
  - Transmits loads with low coefficient of friction
- Labrum
  - Contributes to joint stability
  - Provides suction seal for synovial fluid



Anterior View



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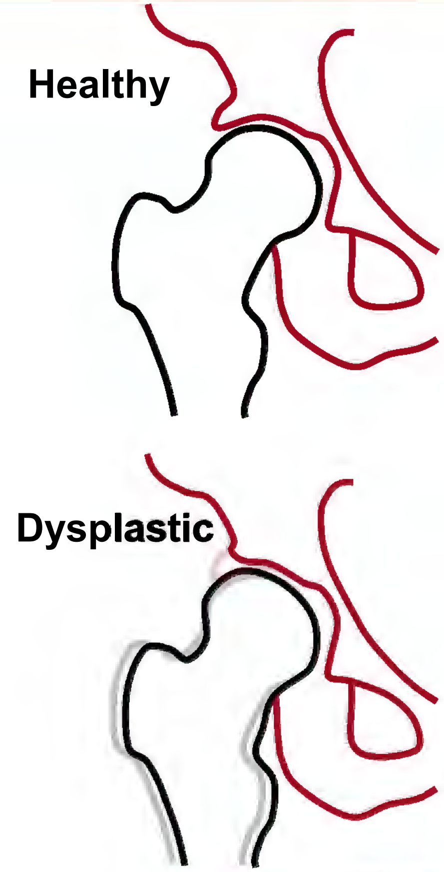
Hip Dysplasia

- Approximately 20% of hip osteoarthritis cases are attributed to morphology associated with hip dysplasia[1]
  - Shallow acetabulum
  - Undercoverage of the femoral head

- Altered cartilage and labral (i.e. chondrolabral) mechanics[2,3]
  - Direct *in-vivo* evaluation of mechanics is not possible
  - Finite element (FE) models investigate the role of hip anatomy in mechanics through the prediction of chondrolabral stresses and strains



[1] Solomon L et al. *J Bone Jt Surg-Ser B.*, 1976; 58(2):176-183. [2] Cooperman D. *J Ped Orthop*, 2013; 33(Suppl1):S2-S7.
[3] Peelle MW et al. *Clin Orthop Relat Res*, 2005; 441:327–333.

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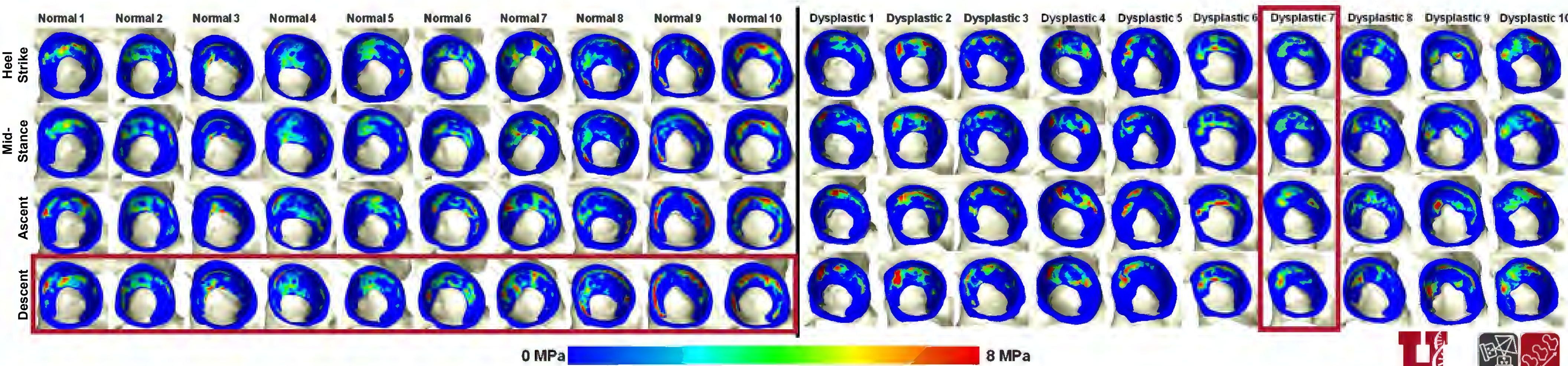
Subject-specific Contact Stress

- Generalized anatomy results in gross underestimations of contact stress and overestimations of contact area[1]
  - Subject-specific anatomy is required for accurate prediction

- Difficult to visualize, compare, and interpret in aggregate form

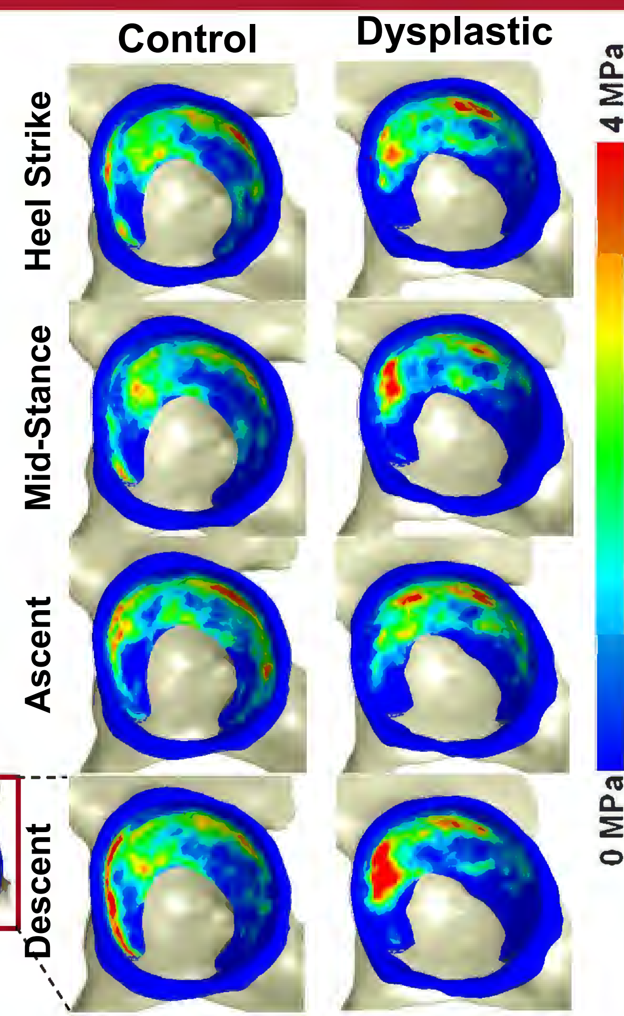


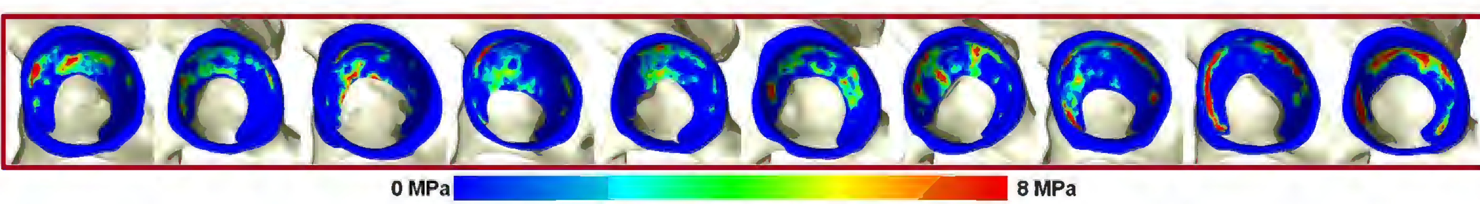
[1] Anderson AE et al. *J Biomech*, 2010; 43(7):1351-1357. [2] Henak CR et al, *Osteoarthritis Cartilage*, 2014; 22(2):210-217.

Group-wise Average Contact Stress

- Descriptive statistics of contact stress
  - Visualize average contact stress fringe plots
  - Qualitative differences → more anterolateral contact and less medial contact in the dysplastic hips

- Quantifying chondrolabral mechanics of dysplasia requires improved analysis methods
  - Preserve patient-specificity of the model through statistical testing

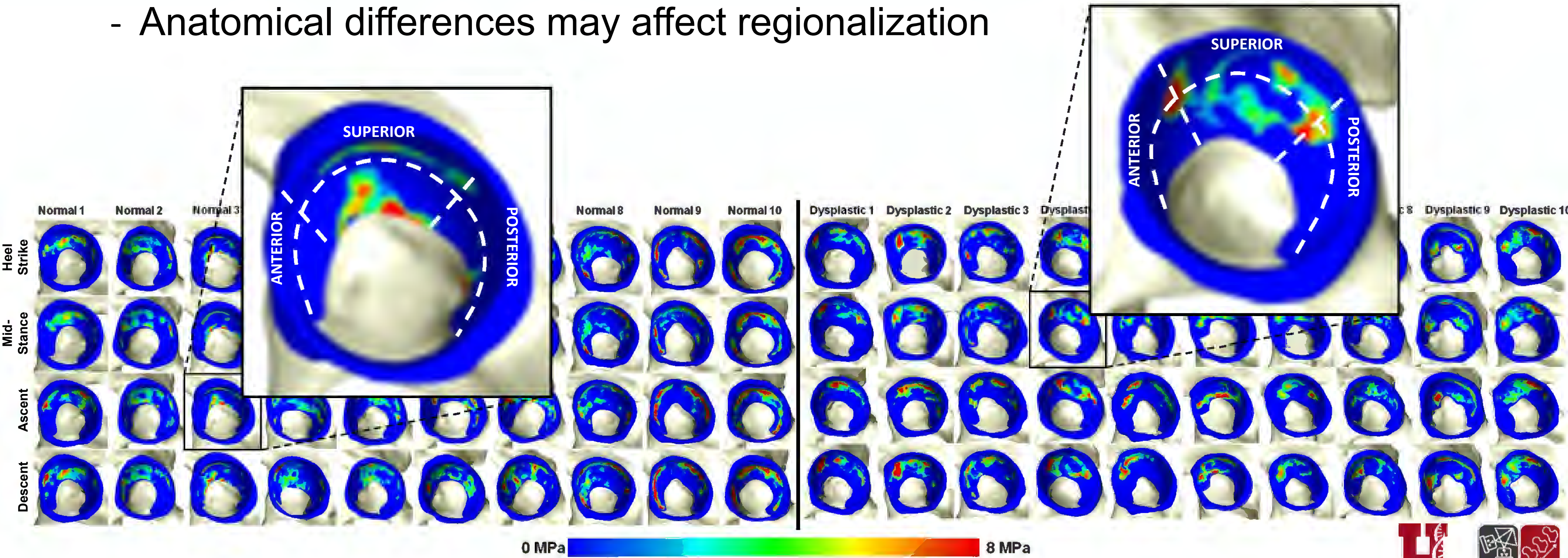




[1] Henak CR et al, *Osteoarthritis Cartilage*, 2014; 22(2):210-217.

Subject-specific Contact Stress

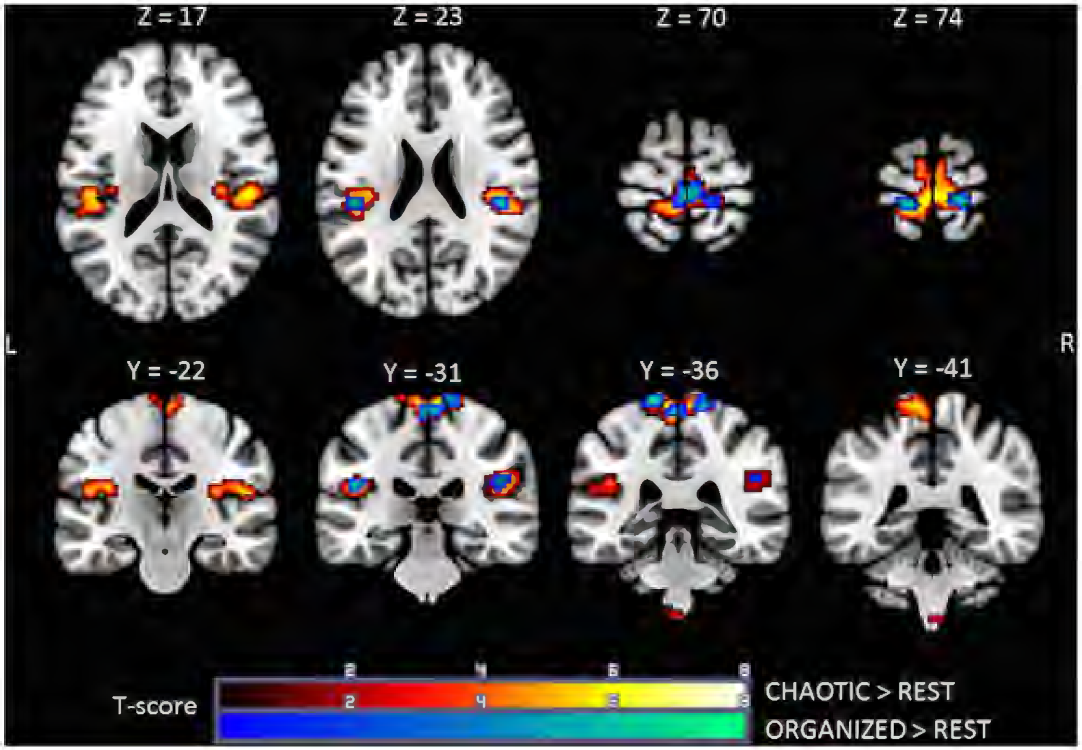
- Sub-dividing anatomy for statistical comparisons
  - Still often requires generalized statistics
  - Anatomical differences may affect regionalization



[1] Henak CR et al, *Osteoarthritis Cartilage*, 2014; 22(2):210-217.

Statistical Parametric Mapping (SPM)

- Technique traditionally applied to functional MRI scans of the brain
  - Spatially extended statistical processes used to test hypotheses about regionally specific effects[1]



[1] Pataky TC, *J Biomech*, 2010, 43(10):1976-82. [2] Labriffe M, *Front Hum Neurosci*, 2017, 11:106.

Motivation and Objective

- SPM is a potential solution to evaluate local variability in mechanics
  - Preserves the subject-specificity of the model through statistical testing
  - Must first establish some correspondence across subjects
    - Correspondence of even complex anatomies can be provided via particle-based statistical shape modeling (SSM)

- **Objective:** Evaluate the combined application of SSM and SPM to compare cartilage contact stress between patients with dysplasia and healthy hips.

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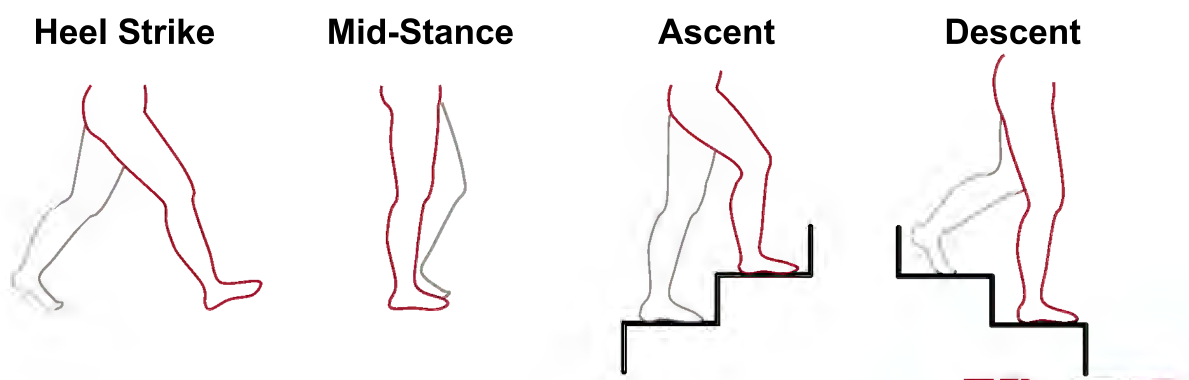
Finite Element Analysis

- Cartilage reconstructions of 20 hip joints previously analyzed with FE[1,2] were incorporated into an SSM using ShapeWorks
  - 10 control, 5 males and 5 females, 26 ± 4 years[1]
  - 10 dysplastic, 3 males and 7 females, 26 ± 6 years[2]

- Modeled activities included:
  - Heel-strike of level walking
  - Mid-stance of level walking
  - Heel-strike of stair ascent
  - Heel-strike of stair descent



[1] Harris MD, *J Orthop Res*, 2012, 30(7):1133-9. [2] Henak CR, *Osteoarthritis Cartilage*, 2014, 22(2):210-7.

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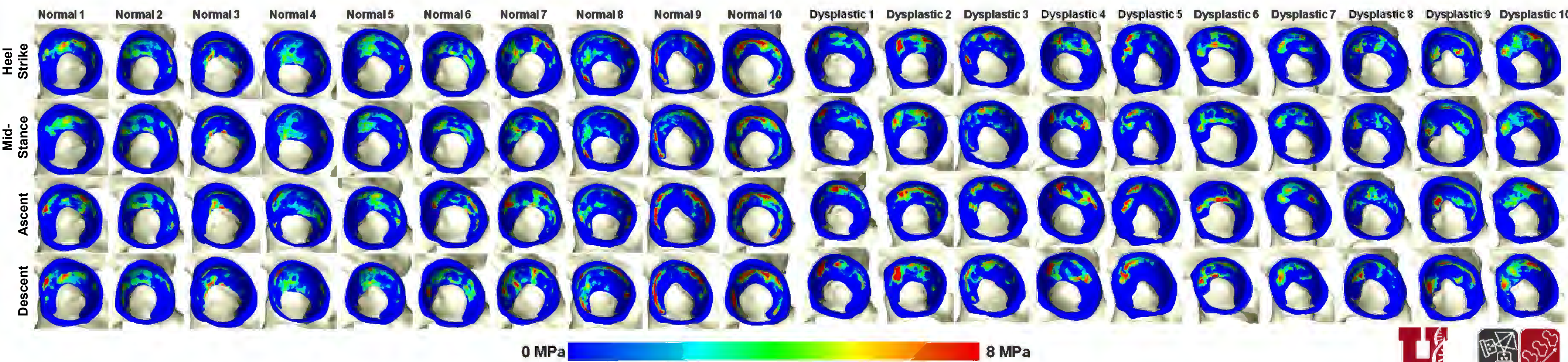

[1] Harris MD, *J Orthop Res*, 2012, 30(7):1133-9. [2] Henak CR, *Osteoarthritis Cartilage*, 2014, 22(2):210-7.

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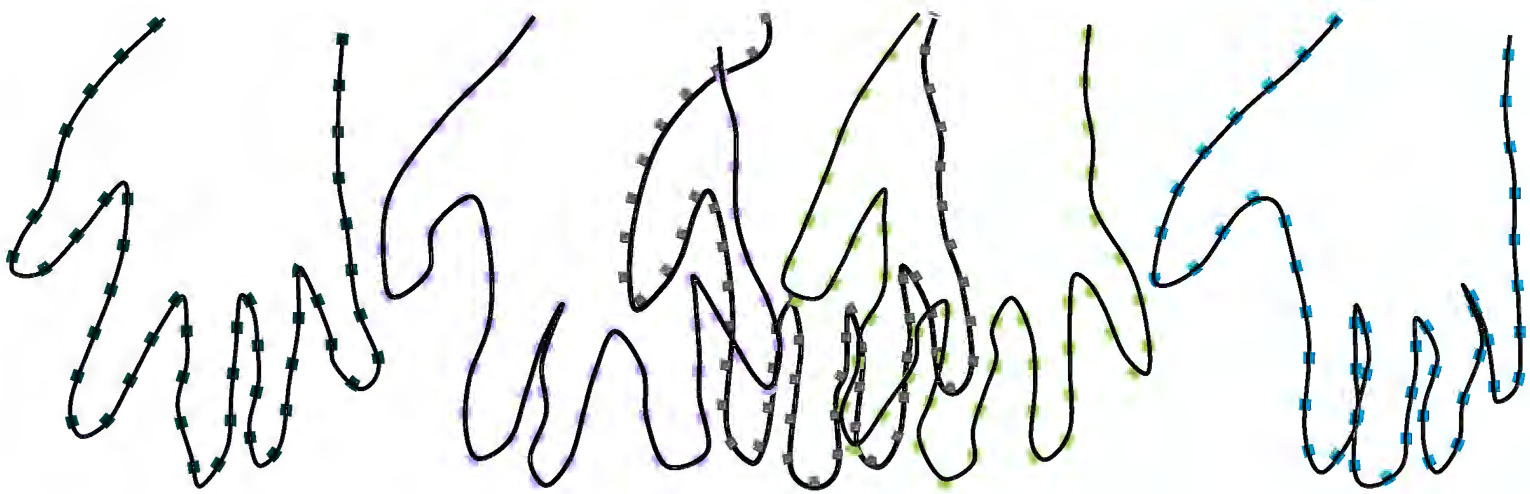
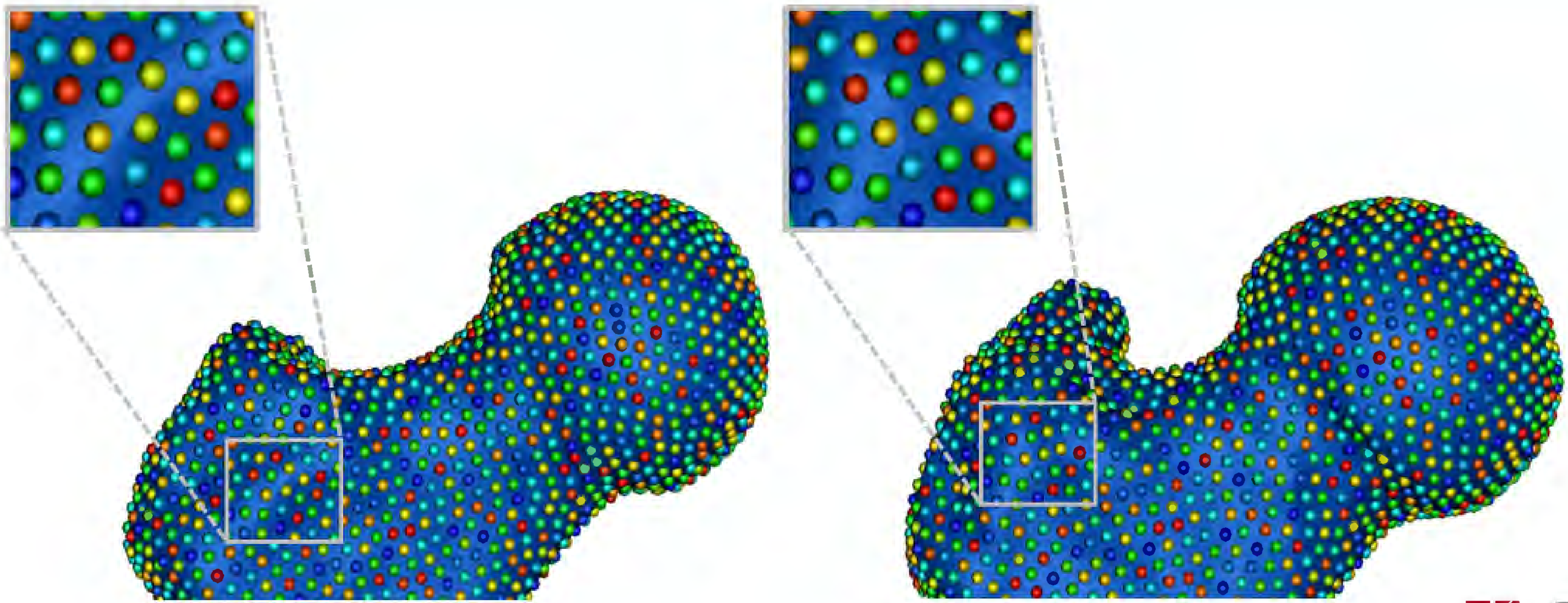
Statistical Shape Modeling

- Correspondence particles represent each shape and are tracked over a set of shapes[1]
- Objectively create mean shape or any standard deviation thereof



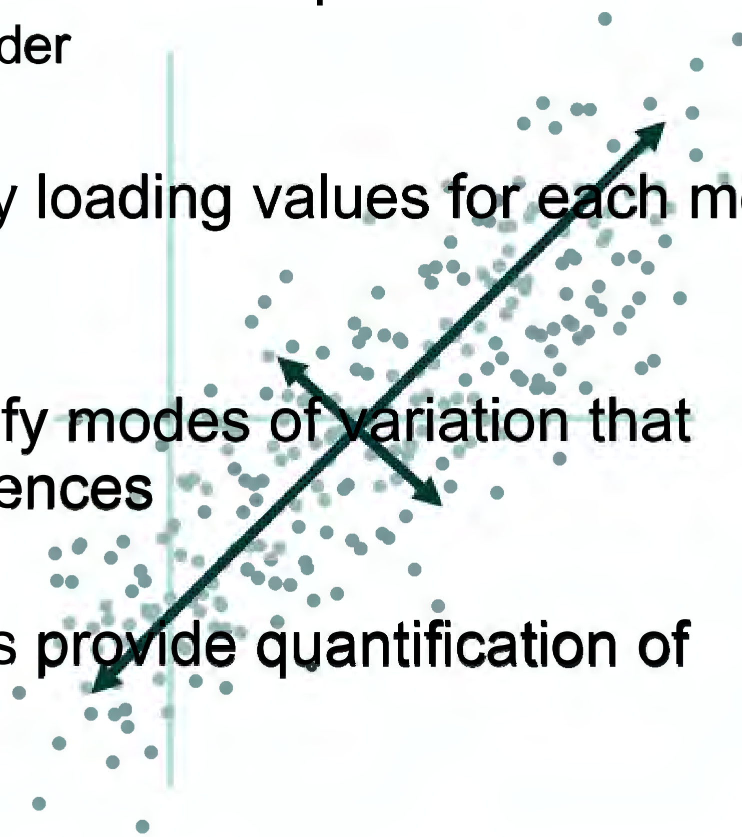
[1] Cates, J. CMICCAI 2008. http://www.sci.utah.edu/software/shapeworks.html

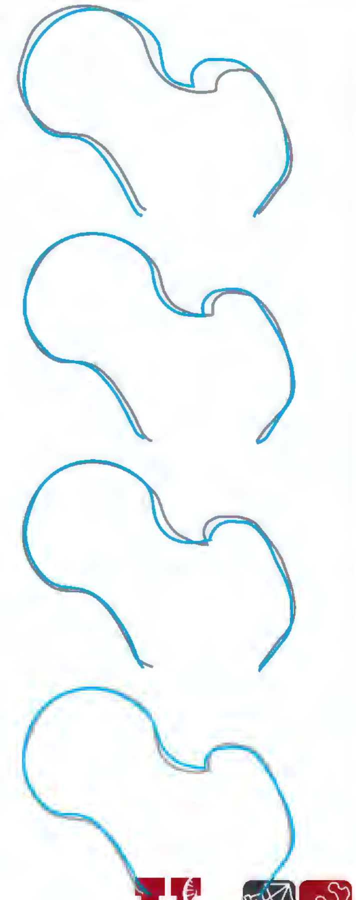
SSM – Correspondence Model



Principal Component Analysis

- PCA allows for the locations of the correspondence particles to be distilled into modes of shape variation
  - i.e. radius and height of a cylinder
- Each shape is represented by loading values for each mode of variation
- The loading values can identify modes of variation that represent overall group differences
- Group-based average shapes provide quantification of shape variation

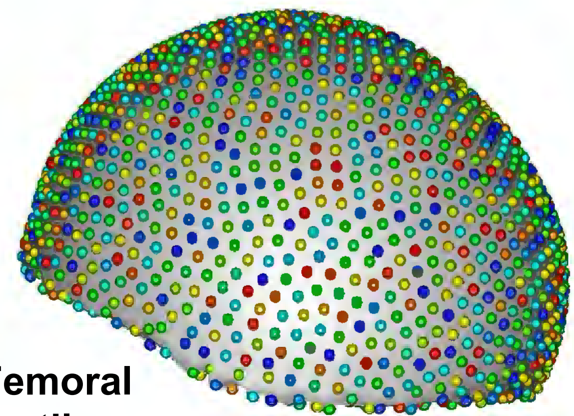




[1] Atkins PR et al., *J Orthop Res*, 2017; 35(8):1743-1753.

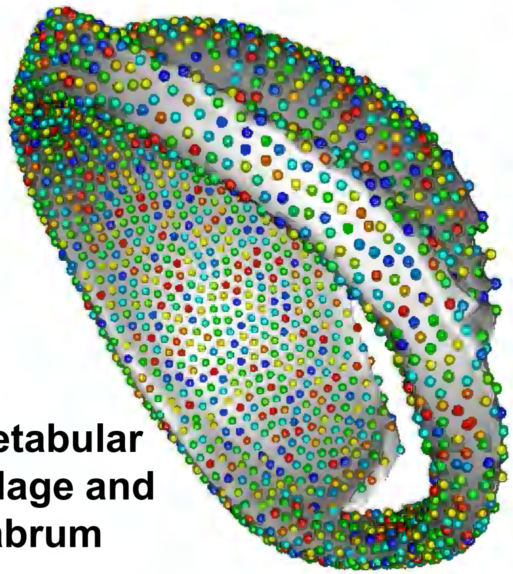
Particle-based Statistical Shape Modeling

- SSMs of the femoral cartilage and acetabular cartilage with labrum were developed independently
  - Surface normals (weighting of 3) and Generalized Procrustes Analysis were used to aid in particle location optimization
  - 2,048 to 3,072 correspondence particles were used dependent on the cartilage mesh type



Femoral Cartilage

Anterior View



Acetabular Cartilage and Labrum

Analysis and Statistical Parametric Mapping

- Principal component analysis (PCA) identified the dominant modes of shape variation for each model
  - Parallel Analysis used to determine modes capturing significant variation
  - Student's T-test used to determine modes which represented significant differences between cohorts

- Contact stress values were evaluated across the cohorts using SPM[1]
  - Two-way ANOVA with single repeated measure used to identify group- and activity-based differences
  - Inference determined significant clusters at p=0.05, 0.025, 0.01, 0.005, 0.001 (n=10,000 permutations)

[1] Pataky TC, *J Biomech*, 2010, 43(10):1976-82.

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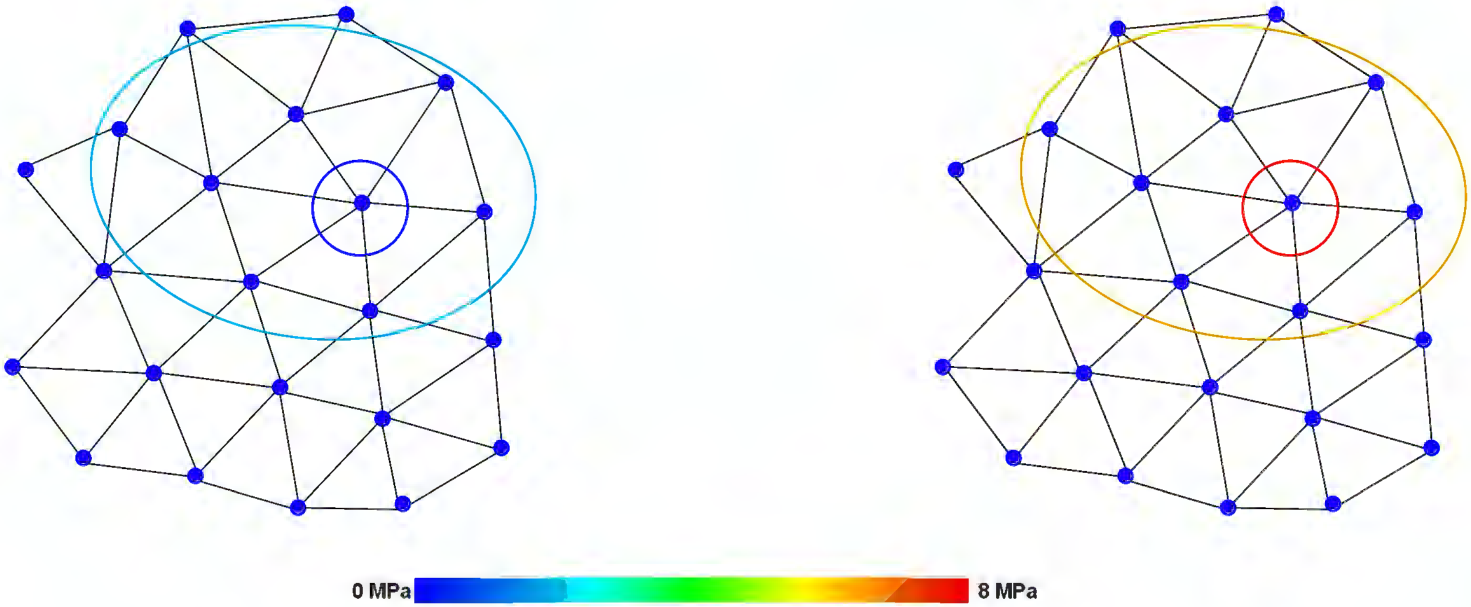
Statistical Parametric Mapping

- Traditional applications expanded to allow for analysis of *n*-dimensional data
  - Spatially extended statistical processes used to test hypotheses about regionally specific effects

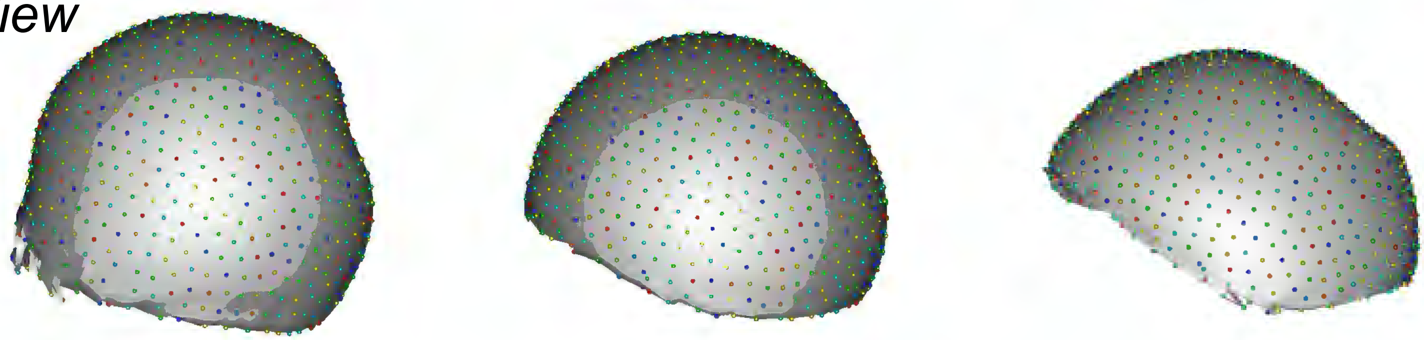


[1] Pataky TC, *J Biomech*, 2010, 43(10):1976-82.

Shape Variation: Femoral Cartilage

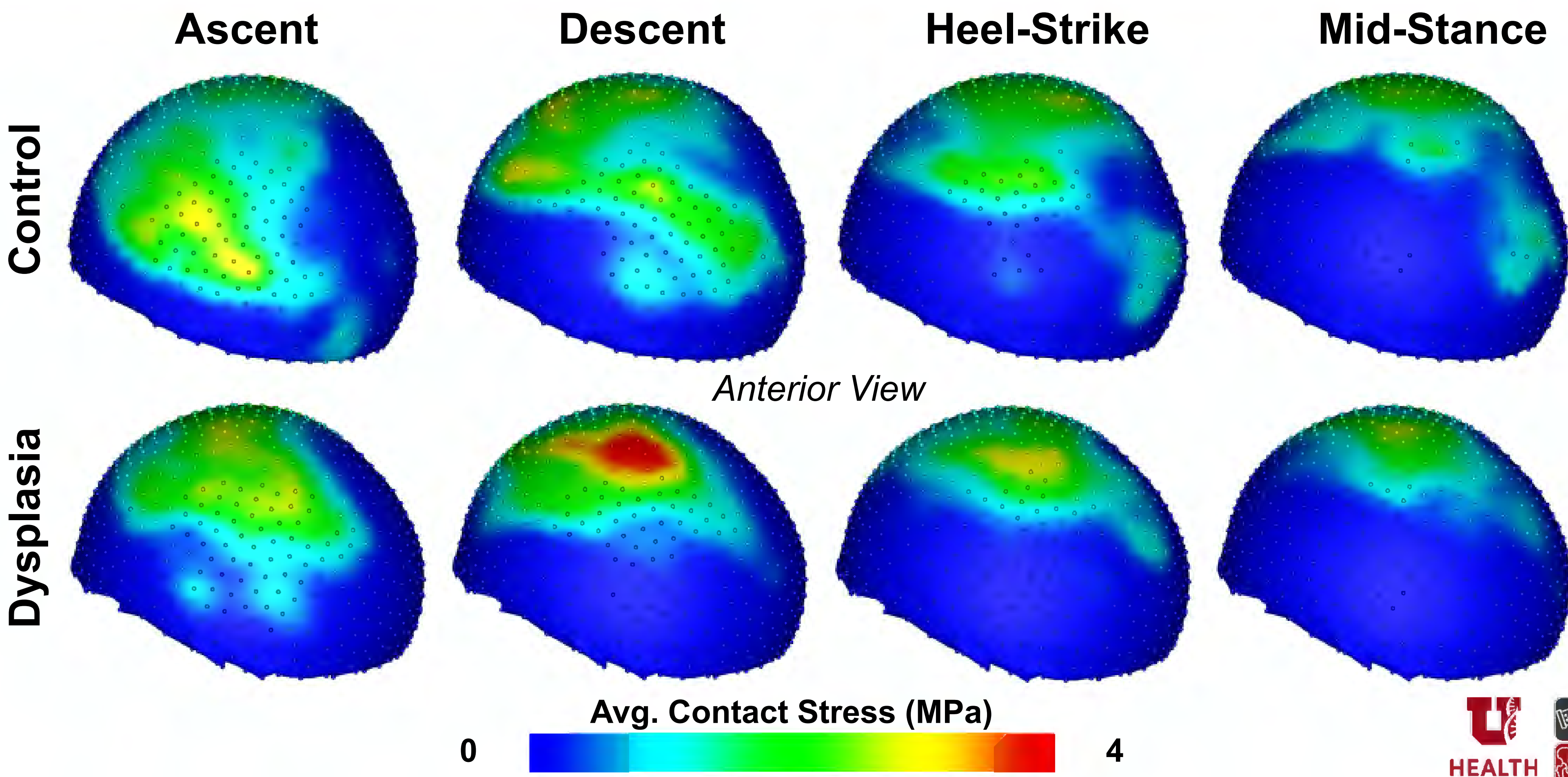
- 1 PCA modes described significant shape variation
  - 75.9% of overall variation
  - Represented significant differences between control and dysplastic cartilage shapes

Anterior View



-2 STD   Mean   +2 STD

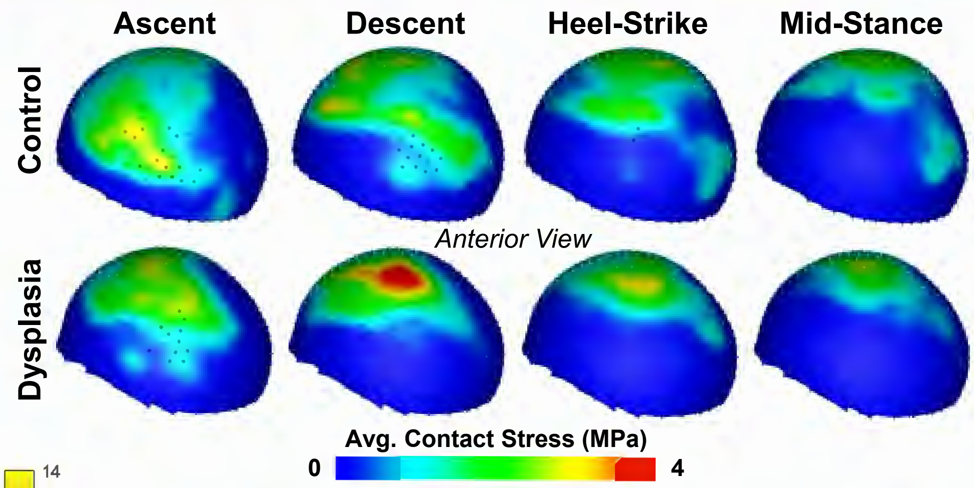
Femoral Cartilage SSM and SPM

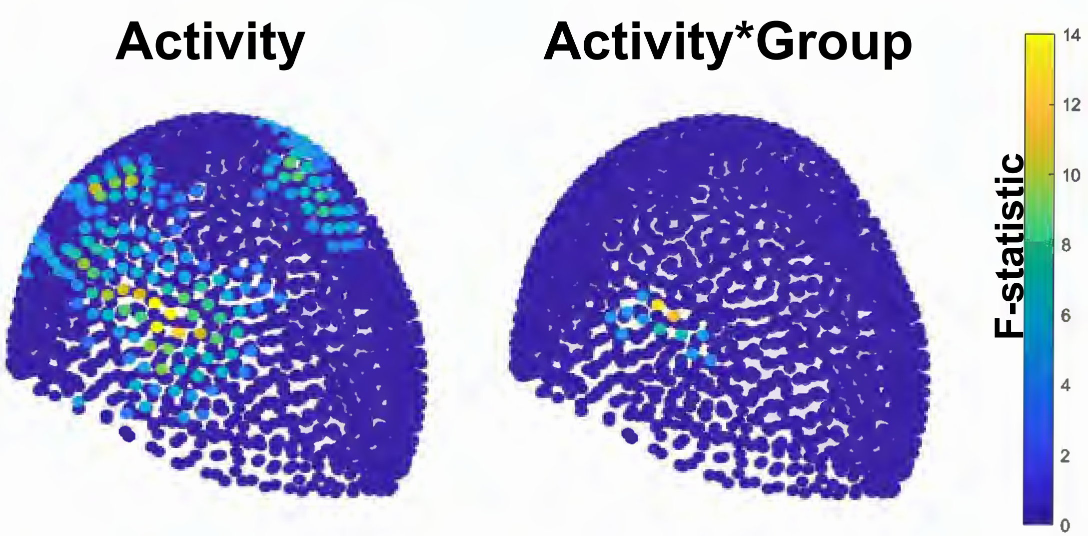


Femoral Cartilage SSM and SPM

- No group-based differences found

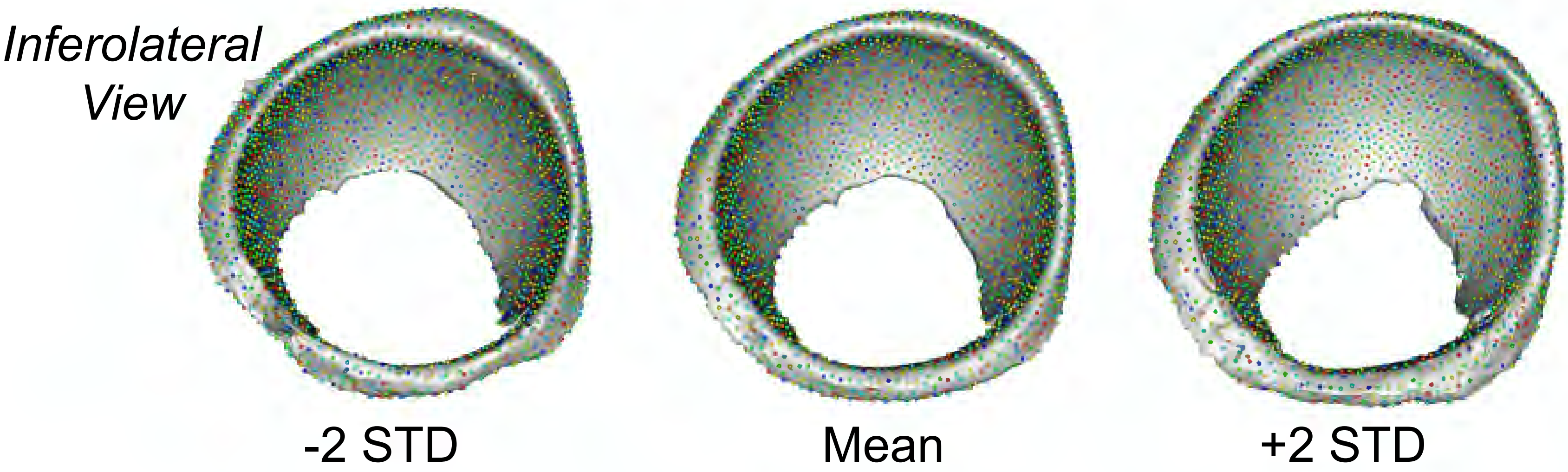
- Clusters of significant variation
  - Activity – 179 particles
  - Activity*Group – 12 particles



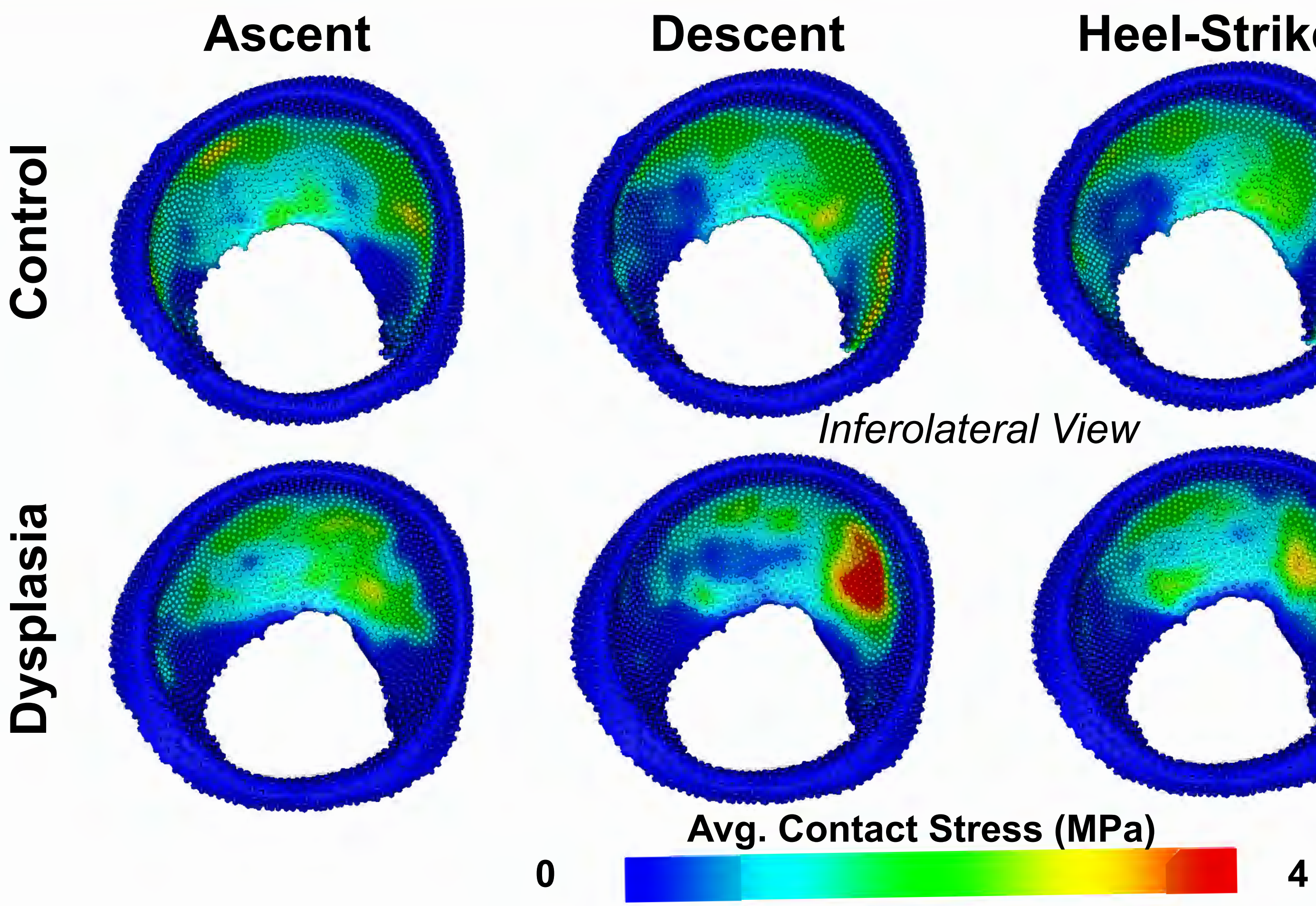


Shape Variation: Acetabular Cartilage and Labrum

- 4 PCA modes described significant shape variation
  - 68.2% of overall variation
  - Mode 1 (40.9% variation) represented significant differences between control and dysplastic cartilage shapes

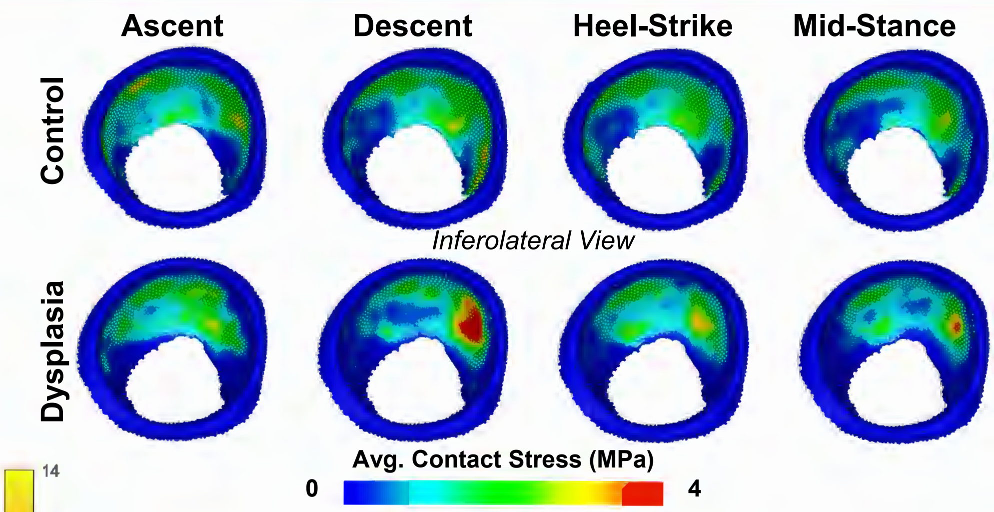


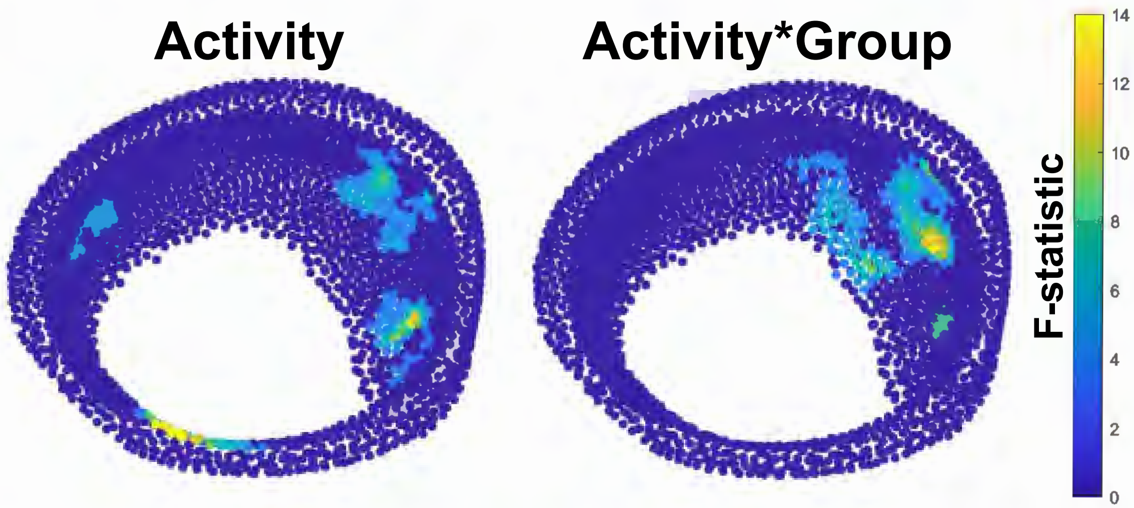
Acetabular Cartilage and Labrum SSM and SPM



Acetabular Cartilage and Labrum SSM and SPM

- No group-based differences found
- Clusters of significant variation
  - Activity – 248 particles
  - Activity*Group – 185 particles





Discussion

- SPM identified regions with differences in contact stress between activities and the interaction between group and activity
  - Application of SPM ensured that local 'hot spots' of contact stress were not diluted through averaging or split between regions

- The small sample size of this study provides a proof of concept for the combination of SSM and SPM to evaluate joint mechanics

- The combined application of SSM and SPM to evaluate cartilage contact stress provides a method to generalize and statistically compare subject-specific mechanics and joint morphology

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

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

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