Integration of Statistical Shape Modeling and Finite Element Analysis for the Study of Hip Pathology

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Introduction

- Femoroacetabular impingement (FAI) and acetabular dysplasia are two pathoanatomical conditions of the hip, and these conditions may be the primary factors leading to osteoarthritis (OA).
- FAI: Restriction of motion caused by osseous deformities, most often sub-grouped into those of the femur (cam), acetabulum (pincer), or both (mixed)[1].
- Acetabular dysplasia: Characterized by an under-contained hip where poor coverage of the femoral head by acetabulum induces excessive motion and overloading of cartilage.

![Figure 1](https://example.com/figure1.png)

Figure 1. (A) Cam FAI: Characterized by bony prominence of anterolateral femoral head; (B) Pincer FAI: Prominence of anterior acetabulum; (C) Mixed FAI: Combined pincer cam impingement.

- Objectives
  - Integrate ShapeWorks with FEBio to enable flexible and robust analyses of shape and function.
  - Quantify the variation in femoral head anatomy and acetabular rim coverage among normal hips and hips with cam/pincer/mixed type FAI.
  - Examine the relation between shape and mechanics in a population of patients with hip dysplasia.

![Figure 2](https://example.com/figure2.png)

Figure 2. (A) Normal Hip: Well covered hip joint with stable femur head; (B) Dysplastic Hip: A "shallow" socket that inadequately covers the femoral head.

Statistical Shape Modeling (SSM)

- SSM quantifies complex anatomy and variation within and between populations of interest extracted from 3D image data[2].
- In SSM, each member of a population is represented by a dense set of correspondence points. Subsequently, statistical analysis is done on the vectors resulting from those point sets.
- ShapeWorks: Software for SSM developed within SCI
  
  www.scl.utah.edu/software/shapeworks.html [2,5].

![Figure 3](https://example.com/figure3.png)

Figure 3. An illustration of the basic concepts the ShapeWorks point-based correspondence optimization.

- Analysis will be performed on CT arthrography (CTA) images of the hip for 50 subjects per group to account for multiple groups (cam/pincer/mixed/normal).
- The output from SSM will be analyzed to understand morphological variability and improve mechanical models for FEA.

![Figure 4](https://example.com/figure4.png)

Figure 4. Shape variations captured in 3 modes: (0) Normal Mode; (1) Medial offset of the femoral head with respect to the posterior slip; (2) Size of femoral head; (3) Curvature of the trochanter.

Finite Element Analysis (FEA)

- FEA predicts patient-specific tissue mechanics [3,4].
- It's a numerical technique for finding approximate solutions to boundary value problems for differential equations.
- FEBio (Finite Elements for Biomechanics): A nonlinear implicit FE framework [www.febio.org] [6].
- FE Model
  - Cortical bone: Discretized into triangular shell elements with position dependent thickness and is represented as linear elastic.
  - Cartilage: Discretized into hexahedral elements and is represented as neo-Hookean hyper-elastic.

![Figure 5](https://example.com/figure5.png)

Figure 5. (A) Color map for cortical bone thickness; (B) FE model of human hip in Preview.

- Population specific FEA is used to predict mechanics such as peak contact stress, contact area, shear stress, etc.

![Figure 6](https://example.com/figure6.png)

Figure 6. Color map of total effective stress in PostView.

Contribution

Mesh Decimation

- Preview: Pre-processor for setting up FE problem for FEBio, supports Mesh decimation.
- Three types of decimation criteria: Scale, Gradient and Clusters

![Figure 7](https://example.com/figure7.png)

Figure 7. (A) Initial mesh; (B) Scaled mesh with half the number of nodes; (C) Scaled mesh with high density at regions with high curvature; (D) Scaled mesh with high density at areas of interest.

Discussion

- Two levels of analysis. First, comparison of all three subgroups of FAI (cam/pincer/mixed) as a single population to the normal subjects. Next, comparison between each sub-group.
- Determine the clinical metrics predictive of FAI related deformities.
- Identify the anatomical variation between normal and dysplastic hips.

References


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