INTRODUCTION

Computational modeling of the spine has become feasible for evaluating new interventions. However, most models reported in the literature represent only a single subject. Using a probabilistic simulation, virtual specimens representing a broad population of subjects may be evaluated. Such an approach has the potential to lead to viable options for pre-clinical evaluation of new interventions in silico. The greatest challenge of applying probabilistic modeling techniques to biological systems is parameterizing the anatomy to capture normal variation across subjects. The present study sought to employ statistical shape modeling (SSM) to parameterize normal variation in lumbar morphology. This study had two specific aims: to develop a SSM of the L3-L4 functional spinal unit (FSU), and to determine if virtual specimens instantiated from the SSM were biomechanically viable. The second aim was addressed by using finite element (FE) modeling to compare facet articulation among instantiated specimens and among specimens reconstructed directly from CT images.

METHODS

Vertebral body geometry was extracted from eight normal CT scans (6 female, 2 male, 54±16yrs) and used to perform statistical shape modeling of the lumbar spine. Three distinct shape models were constructed: one for L3 alone, one for L4 alone, and a third model for L3-L4 matched sets. For each SSM, a principal component analysis (PCA) was performed on the system covariance matrix. In PCA, eigenvalues of the covariance matrix quantify variance of shape along each of the eigenvectors, which are the principal modes of shape variation. Any one of the specimens modeled by SSM may then be expressed as,

\[ P = P_{mean} + \sum p_i b_i * c_i \]  

where \( P_{mean} \) represents the mean of all specimens in the particular SSM, the \( b_i \) are scalar coefficients, and the \( c_i \) are the eigenvectors computed from PCA. Each individual specimen was represented by a unique combination of the \( b_i \) coefficients, which were assumed to be normally distributed across specimens. To instantiate a new virtual specimen the normal distribution for each \( b_i \) coefficient was randomly sampled.

It is known that spine biomechanics are sensitive to facet articulation, so a preliminary FE evaluation was performed to confirm that specimens instantiated from a SSM produced facet articulation similar to the natural spine. Three groups of FE models were constructed: four L3-L4 FSU’s were arbitrarily chosen from the original eight sets of CT image data (natural), four virtual specimens were randomly instantiated from the SSM constructed with L3-L4 matched sets (FSU), and four virtual specimens were created by independently instantiating L3 and L4 bodies from their respective SSM’s (L3/L4).

Each FE model contained eight ligaments (non-linear springs [4]), an intervertebral disc (hyperelastic annulus, fluid cavity for nucleus), and linear elastic cartilage (2mm thick on each facet). The FE model was validated using previously reported range of motion data [5]. In the present study each specimen was loaded with an 800 N compressive follower load [5] and 7.5Nm of right axial rotation. Axial rotation was chosen because it loaded the lumbar facets directly and provided a good basis for comparison of facet contact among the three groups of specimens. FE models were solved with Abaqus/Explicit (SIMULIA, Providence, RI).

RESULTS

For each SSM the first five principal components (PC) of size and shape variation captured approximately 95% of the variance in the data. The first three shape modes for L3 are illustrated in Figure 1. PC1 was a scaling mode. PC2 was associated with shape and angulation of the facet joints. PC3 produced variations in the transverse processes. Higher modes were not visually obvious. Shape modes for the other SSM’s were similar to L3.

The virtual FSU specimens instantiated from the SSM based on L3-L4 matched sets exhibited noticeable shape variation but facet joints appeared to mate qualitatively similar to natural specimens (Figure 2a,b). The L3/L4 specimens constructed from independent shape models of L3 and L4 exhibited unacceptable facet mating and it was obvious that they were not viable for FE simulation (Figure 2c).

DISCUSSION

Statistical shape modeling was applied to characterize morphological variations in the lumbar spine. The dominant modes of shape variation were associated with overall scaling as well as angulation of the facets and transverse processes. Future work will investigate correlations among these fundamental modes of shape variation and direct measures of size/shape that may be estimated from simple 2D images.

Virtual specimens instantiated from a SSM of the L3-L4 FSU were found to exhibit facet articulation similar to natural specimens. The L3/L4 models constructed by mating L3 and L4 bodies instantiated from independent shape models exhibited unacceptable facet interaction. This suggests that a SSM for the full lumbar spine must account for size and shape variation across all bodies (L1-L5) simultaneously. Such a model is the focus of ongoing work and will be incorporated into a probabilistic framework to evaluate lumbar biomechanics across a population of virtual subjects.

The SSM training set was limited to eight CT scans in the present study. Future work will expand this number, but we believe the findings with respect to facet articulation remain valid for any size training set.

REFERENCES