Stepwise Development of a Finite Element Model of the Lumbar Spine

INTRODUCTION

Validated finite element (FE) models of the functional spinal unit (FSU) and lumbar spine are essential in design-phase device development and in assessing the mechanics associated with normal spine function [1] and degenerative disc disease (DDD) [2], as well as the impact of fusion and total disc replacement (TDR) [3]. Although experimental data from fully intact specimens can be used for model tuning or validation, the contributions from the individual structures (disc, facets, and ligaments) may be inappropriately distributed. Hence, creation of decompression conditions or device implantations that require structure removal may not have the proper resulting mechanics. Accordingly, the objective of the present study was to perform a stepwise development of an explicit FE model of the lumbosacral spine and the functional spinal unit (FSU) L4-L5 using specimen-specific in vitro data which includes the sequential transection of each structure.

METHODS

Mechanical testing was performed on L1-S1 and FSU L4-L5 from a 71 year old male specimen in flexion-extension, lateral bending, axial rotation, and combined motions using a custom multi-axis spine motion simulator [4]. Segmental spinal motions were tracked while force and moment reactions were recorded at the fixed end (Figure 1). Testing of the L4-L5 FSU followed a sequential transection protocol to evaluate the contribution of the transected structures to the overall mechanical stability of the segment. The intact FSU was tested under 10 N-m pure moment conditions followed by removal of the following structures, in order: supraspinous ligament (SSL), intraspinous ligament (ISL), posterior longitudinal ligament (PLL), anterior longitudinal ligament (ALL), facet capsule, and facet joints. The FSU was evaluated after each transection using a hybrid approach, which applied the rotation from the intact pure moment condition and measured the moment required. Explicit FE models of the lumbar spine and L4-L5 FSU were constructed from a series of coronal computed tomography (CT) images using ScanIP (Simpleware, Exeter, UK) (Figure 1). Based on the dissected geometry, the IVD included three regions (anterior, posterior and laterals) modeled as 8-noded hex elements representing the annulus fibrosus (AF) and a fluid-filled cavity representing the nucleus (Figure 1). The regions of the annulus were represented as anisotropic hyperelastic (Holzapfel material model, with material constants: C_{ij}, D_i, k_i, k_3 and kappa). The ligaments were modeled by multiple nonlinear, tension-only connector elements in series and parallel. For these analyses, the vertebral bodies were considered rigid.

FE analyses using Abaqus/Explicit (Simulia, Providence, RI) were performed according to the protocol followed in the experiment. Initially, a model with disc only was created and AF material properties optimized to represent the experimental data. Automated optimization was performed using a simulated annealing algorithm in Isight (Simulia, Providence, RI) to match the reaction moment measured during this hybrid test (Figure 2). Subsequently, each individual structure (facets, facet capsule, ligaments) was added to the model and automated optimization was utilized to tune material properties, thus assuring contributions from each structure are appropriate. After stepwise tuning of the FSU, material properties were applied to the L1-S1 lumbar models.

RESULTS

Reaction moments from FE analyses were well-matched to the experimental data using simulated annealing optimization (Figure 2) at each step of the protocol. The deformable analysis required approximately 20 minutes of computational time, depending on the structures included, and on average 200 optimization iterations were required. The anisotropic hyperelastic material with three regions was able to effectively represent the annulus fibrosus during flexion-extension, lateral bending and axial rotation loading conditions (Figure 2). Predicted torque-rotation (Figure 2) results were very similar for FE analyses and experiments; predictions showed a root mean square difference of 0.25° in rotation compared to the experiment (averaged over all loading conditions). Stepwise addition of structures to the FSU and the tuning at each configuration successfully represented experimental reaction moment, with an average error of 0.4 N-m (Figure 3).

DISCUSSION

Developing the explicit FE model in a stepwise fashion ensures that the contribution of each structure is appropriate; the resulting validated model can successfully simulate decompression and other surgical conditions, and be used to address clinically relevant questions related to individual structures. Ligamentous properties were the most straightforward to optimize, while the disc and particularly facet cartilage positioning were more difficult. Precise specimen-specific facet cartilage geometry and alignment were required to reproduce the measured experimental constraint.

SIGNIFICANCE

The systematic development process results in validated FSU and L1-S1 models with appropriate contributions from the various structures.

REFERENCES


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