Efficient Probabilistic Finite Element Modeling for Evaluation of Spinal Mechanics

INTRODUCTION:
Patient-specific finite element (FE) models of the spine can provide assessments of mechanics associated with normal spine function [1] and degenerative disc disease (DDD) [2], as well as the impact of fusion, total disc replacement (TDR) and facet arthroplasty treatments [3]. A typical implicit FE computational methodology is ideal for performing parametric evaluations of various properties and treatments; however, analysis time can make large probabilistic studies or representation of a population of patients impracticable. An explicit FE formulation may be advantageous due to efficiency in handling complex, changing contact conditions and the ability to evaluate either rigid or deformable body contact. Probabilistic studies based on these deterministic FE formulations are of great interest currently as model input parameters (such as properties of nucleus, annulus and facet, ligament stiffness and reference strain) have been characterized experimentally, but contain substantial variability. The gold standard probabilistic methodology, Monte Carlo simulation, is computationally expensive, typically requiring hundreds of analyses. Recent work has shown progress in application of efficient probabilistic techniques requiring far fewer analyses [4], and may be appropriate for evaluation of spine mechanics. Accordingly, the objectives of the present study were to develop a computationally efficient, probabilistic explicit FE model of the lumbar spine, to evaluate force-displacement characteristics, contact mechanics and efficiency for a functional spinal unit (FSU) L3/L4 using implicit and explicit FE model representations, and to assess the capability of efficient probabilistic analyses to predict performance incorporating disc and ligament material variability.

METHODS:
An explicit FE model of the lumbar spine of a normal adult subject was constructed from a series of coronal computed tomography (CT) images. The model incorporated intervertebral bodies L1 through L5 separated by intervertebral discs (IVD), all seven ligaments (anterior & posterior longitudinal (ALL & PLL), interspinous (ISL), intertransverse (ITL), supraspinous (SSL), facet capsular (FCL), and ligamentum flavum (LFL)) and articulating facet contact (Figure 1). The vertebral bodies and articular facet cartilage were meshed with 8-noded hexahedral elements. The IVD comprised of four concentric layers modeled as 8-noded hexahedral elements representing the annulus and a fluid-filled cavity representing the nucleus. Ground substance was assumed to be hyperelastic (Neo-Hookean) [5]. Fibers embedded in the disc and ligaments were modeled by multiple nonlinear, tension only spring elements in series and parallel. Spring stiffness was adjusted to match force-deflection behavior [6] in a separate analysis. All bones were considered rigid for the force-displacement evaluations.

To evaluate the FE methods, implicit and explicit analyses (Abaqus, Dassault Systems, Providence, RI) of the L3/L4 FSU were performed (Figure 1). The implicit analysis used a fully deformable (FD) representation of the facet cartilage, while two explicit models were developed, including FD and a computationally efficient (CE) representation with the facets as rigid bodies with an optimized pressure-overclosure relationship. For the FD analyses, the facet cartilage was modeled as linearly elastic (E=20 MPa, Poisson’s ratio=0.45) [7]. In these FSU analyses, L4 was constrained with a 3500 N compressive load applied to L3 for compression and a pure moment of 10 Nm applied to L3 for flexion-extension. Resulting force-deflection and torque-rotation curves were compared for each of the three analyses.

Probabilistic analyses were performed using custom scripting and NeuroMuscle (SwRI, San Antonio, TX) and incorporated mechanical property variability. Linear stiffness for the IVD fibers and all ligament bundles were normally distributed with mean values based on a previous verification study and standard deviations equal to 30% of the mean value for stiffness [8]. Monte Carlo (MC, 500 trials) and Advanced Mean Value (AMV) analyses were conducted for compression and flexion-extension loading conditions. The probabilistic analyses provided a distribution of predicted laxity (5 and 95 percentile bounds) as well as sensitivity of each output measure to the ligament and fiber input parameters. Predicted bounds and sensitivities were compared for the two probabilistic methods.

RESULTS:
Predicted force-deflection and torque-rotation (Figure 2) results were nearly identical for the implicit and explicit FE analyses; explicit predictions showed an average root mean square difference of 0.023 mm in translation and 0.068° in rotation compared to the implicit analysis. The computational time for the deformable explicit analysis during flexion-extension was approximately 35% of the time required for the implicit analysis, while the computationally efficient explicit model required only 5.2%. In addition, contact locations and pressure distributions in the facet cartilage predicted by the CE model were an excellent representation of the fully deformable results (Figure 2 Inlay), with peak pressures differing by less than 0.15 MPa. The force-deflection and torque-rotation bounds predicted using MC simulation with 500 trials agreed well with the AMV results based on only 20 trials.

DISCUSSION:
The explicit FE representation offers potential advantages in that either the deformable or rigid body analysis can be run from the same input file, providing efficiency options and equivalent force-deflection and torque-rotation predictions as the fully deformable implicit analysis. The rigid body analysis, at ~5% of the implicit analysis time, provides excellent potential for large-scale probabilistic studies evaluating effects of TDR alignment or property variability. The AMV method accurately estimated the results from the MC simulation in only 4% of the time. The probabilistic spine model can be used to efficiently evaluate mechanical changes in the segment (and adjacent segments) associated with DDD, as well as fusion, flexible fusion and TDR treatments.

REFERENCES: