Validation of an Automated Method for Generating Subject-Specific Finite Element Models of the Lumbar Spine

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Introduction: Historically, subject specific finite element (FE) models have been very labor intensive to create [1]. Recently, an automated method has been developed to generate subject specific FE models of the lumbar spine [2] from medical image data. Such models not only allow personalized biomechanical analysis, but they also provide detailed geometric data to facilitate statistical shape modeling and probabilistic simulation for population-based investigations. Taken together, these modeling tools have numerous applications from pre-clinical testing of implants and surgical interventions to predictions of tissue-level biomechanical metrics in affected populations, such as persons with a lower limb amputation. In order to use FE models for these applications it is important to be confident in the accuracy of the results they produce. Validation is an important step in ensuring the accuracy of any FE model. The purpose of the current study was to validate the kinematics of an automatically generated subject-specific full lumbar spine model to experimentally measured motion.

Methods: Experimental data were collected for a full lumbar (L1-S1) specimen in flexion/extension, left/right lateral bending, and left/right axial rotation [3]. Bone surface geometry for the experimental full lumbar specimen was obtained from CT scans and used as input for an automated mesh morphing and FE model generation procedure. The automated method identifies attachment points of all ligaments, creates discs based on end plate geometry, and creates facet cartilage contact surfaces. The details of the automated method have been published previously [2]. Material properties were assigned based on a previously calibrated deterministic model [3]. The resulting automatically generated FE model was tested in quasi-static flexion/extension, left/right lateral bending, and left/right axial rotation to match the experiment. A pure torque increasing from zero to 8 Nm was applied to the model over 3 seconds in each case. Flexion and extension also included a follower load of 450 N for one second prior to the application of torque. Torque rotation data were collected for each spinal level in the model for each DOF tested and compared to the experimental results.

Results: Figures 1-3 show the comparisons between the experimental results and the simulations for overall L1-S1 flexion/extension (F/E), left/right lateral bending (L/R Bending), and left/right axial rotation (L/R Rotation), respectively. The root mean squared (RMS) error between measured and predicted rotations for the full L1-S1 model was 3.2°, 1.7°, and 2.0° for F/E, L/R Bending, and L/R Rotation, respectively. The rotation error at the level of each individual motion segment was also examined and was found to be 0.58°, 0.20°, and 0.36° for F/E, L/R Bending, and L/R Rotation, respectively.

Discussion: The torque-rotation curves from the automatically generated FE model compared well to the experimental measurements. This validation shows that the methods for auto-generating the FE model reproduce experimentally measured kinematics with good accuracy. The RMS errors and Figures 1-3 illustrate that the highest error in the validation was for flexion / extension and the lowest error was for lateral bending. The excellent agreement at the level of the individual motion segments
demonstrates that the model not only predicts kinematics well for the overall L1-S1 endpoints, but that
the deformed configuration of the model also matches the experiment well across all levels. The focus
of this study was validation of only the automated segmentation, meshing, and FE model generation
procedure, with the latter step comprising automatic construction and placement of all soft tissues on
the lumbar model. When performed manually, these model generation steps are subject to inter-
operator variability, and they require a substantial time commitment. The automated procedure
demonstrated here is based on automatic bone landmark detection, and it produces consistent
graphy with reliable landmark correspondence from specimen to specimen in only about 1.5 hours
compared to weeks/months for manual model creation. Material properties used in this study were
taken from a prior calibration [3]. Such properties are tedious to measure in vitro and difficult or
impossible to estimate in vivo. In this first step of model validation we have deliberately decoupled
automatic geometry and FE generation from material property selection (by relying on previously
calibrated material parameters [3]), but appropriate parameterization of soft tissue material models
remains an important next step in the validation workflow. Future work will focus on better
understanding the sensitivity of FE predictions to variations in material properties associated with
factors such as age and degeneration.

**Significance:** Validation and automation are critical steps in the process of making FE models effective
for clinical applications. The current study shows that our automated method can be used to create a
full lumbar FE model of a specific specimen and produce kinematics consistent with experimental
measurement. With robust validation (ongoing), this automated technique may be used to effectively
leverage existing CT databases to interrogate subject-specific lumbar biomechanics on a large scale.
Landmark data extracted from subject-specific models may also facilitate statistical shape modeling and
probabilistic analysis for pre-clinical evaluation of spinal implants across a virtual population of patients.
Figure 3. Simulation (Sim) and experimental (Exp) results for L1-S1 in Axial Rotation.
Figure 1. Simulation (Sim) and experimental (Exp) results for L1-S1 in Flexion / Extension.
Figure 2. Simulation (Sim) and experimental (Exp) results for L1-S1 in Lateral Bending.