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Automated finite element meshing of the lumbar spine: Verification and validation with 18 specimen-specific models

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ABSTRACT

The purpose of this study was to seek broad verification and validation of human lumbar spine finite element models created using a previously published automated algorithm. The automated algorithm takes segmented CT scans of lumbar vertebrae, automatically identifies important landmarks and contact surfaces, and creates a finite element model. Mesh convergence was evaluated by examining changes in key output variables in response to mesh density. Semi-direct validation was performed by comparing experimental results for a single specimen to the automated finite element model results for that specimen with calibrated material properties from a prior study. Indirect validation was based on a comparison of results from automated finite element models of 18 individual specimens, all using one set of generalized material properties, to a range of data from the literature. A total of 216 simulations were run and compared to 186 experimental data ranges in all six primary bending modes up to 7.8 Nm with follower loads up to 1000 N. Mesh convergence results showed less than a 5% difference in key variables when the original mesh density was doubled. The semi-direct validation results showed that the automated method produced results comparable to manual finite element modeling methods. The indirect validation results showed a wide range of outcomes due to variations in the geometry alone. The studies showed that the automated models can be used to reliably evaluate lumbar spine biomechanics, specifically within our intended context of use: in pure bending modes, under relatively low non-injurious simulated *in vivo* loads, to predict torque rotation response, disc pressures, and facet forces.

1. Introduction

Finite element (FE) modeling of the lumbar spine holds promise for pre-clinical evaluation of new devices, but subject-specific modeling and simulation remain challenging due to the uncertainty of material properties and boundary conditions (Dreischarf et al., 2014). Alternatively, population-based modeling has the potential to offer information on device efficacy across a broad range of virtual patients, and parameter uncertainty can be accommodated with well-established probabilistic methods. Modeling a large number of subjects to represent a target population has been impractical, however, due to the complexity of spinal geometry and the time consuming process of model creation. A new method for automatic generation of FE meshes of the lumbar spine addresses this limitation (Campbell and Petrella, 2015), but it has not been formally evaluated, which was the focus of the present study.

Verification and validation (V&V) are the primary methods for evaluating the reliability and accuracy of an FE model within its context of use. Several papers have been written in the last decade highlighting the importance of V&V and providing guidelines for these methods in the field of biomechanics (Anderson et al., 2007; Erdemir et al., 2012; Henninger et al., 2010; Viceconti et al., 2005). These authors have also helped to reinforce a standard vocabulary around V&V. Namely, verification is the process of confirming the computational methods solve the governing equations correctly and accurately. Validation involves evaluating how accurately the model simulates the real physical system of interest.

Jones and Wilcox (2008) presented a specific framework for V&V in the spine, and highlighted the importance of presenting verification results in the form of FE mesh convergence. However, relatively few studies based on segment FE models of the spine have reported detailed investigations of mesh convergence. Some studies of the lumbar spine have evaluated the FE mesh qualitatively (Eberlein et al.,

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2004, 2001; Tsouknidas et al., 2013), but the study by Ayturk and Puttlitz (2011) is one of the few to report a detailed quantitative mesh convergence analysis. They evaluated a multi-segment lumbar spine model using multiple bending modes and outcome metrics with a convergence criterion of 5%.

Most validation studies for segment FE models of the spine have also used indirect validation (Jones and Wilcox, 2008). Indirect validation for a spine FE model usually involves comparing FE output metrics to a range of experimental data from multiple specimens to demonstrate that the FE predictions fall within a reasonable experimental spread. This is in contrast to direct validation which typically involves developing an FE model of a specific specimen and comparing FE results to experimental data from the same specimen. Direct validation of segment models of the spine presents significant challenges as both the geometry and material properties of a specific specimen need to be known to develop an accurate subject-specific FE model.

The purpose of the current study was to seek broad verification and validation of lumbar spine FE models created using a previously published automated algorithm (Campbell and Petrella, 2015). We defined our context of use as: prediction of torque-rotation response, disc pressure, and facet force in flexion/extension, axial rotation, and lateral bending, under typical *in vivo* simulated loads. A detailed, quantitative mesh convergence study was conducted to verify appropriate mesh density created by the automated method. Semi-direct validation was performed by using calibrated material properties and precise boundary conditions for a single specimen from a prior experimental study (Coombs et al., 2013; Rao, 2012). A thorough indirect validation was also performed for 18 full lumbar FE models using generalized material properties and a range of experimental outcomes reported in the literature.

2. Materials and methods

2.1. FE model details

Briefly, the automated algorithm used to create the FE models in this study accepts STL geometry of lumbar vertebrae as input and identifies 1306 landmarks characterizing the key biomechanical features of each bone, such as endplate contours, ligament attachment points, and facet contact surfaces. Landmark data are then used as the basis for automated fitting of a pre-existing template FE mesh (Coombs et al., 2013; Rao, 2012) to the subject-specific bone geometry. All models are oriented with the vertical axis of L4 aligned with gravity. Lastly, soft tissues are also added to create a complete Abaqus (Simulia, Johnston, RI, USA) FE model of the specimen. The automated algorithm runs in Matlab (MathWorks, Natick, MA) and requires approximately 90 minutes to complete for a typical multi-segmental lumbar specimen (L1–L5). Additional details of the automated methods may be found in (Campbell and Petrella, 2015).

Three specific workflows were used to evaluate the FE models created by the automated algorithm (Fig. 1). Specimen geometry, material properties, and the FE solver were chosen deliberately for efficiency and for direct comparison to previous work where appropriate. A single representative L4–L5 functional spinal unit (FSU) was used for mesh convergence (Fig. 1a). Semi-direct validation was performed using the automated method with bone geometry and calibrated material properties (Fig. 1b), both of which were obtained from a prior study (Rao, 2012). And, indirect validation was based on a comparison of results from automated FE models of 18 individual specimens to a range of data from the literature (Fig. 1c). For mesh convergence and indirect validation, a set of generalized material properties was synthesized from the literature (Table 1).

The bones and endplates were represented by 7470 elements total for each vertebra and were modeled as rigid, similar to several previous studies (Cegoñino et al., 2014; Coombs et al., 2013; Dreischarf et al., 2014; Little et al., 2007; Moramarco et al., 2010; Rao, 2012). Since the bone elements were rigid, their only function in the model was for visualization of the bone surface and confirmation of correct soft tissue attachment. Seven relevant spinal ligaments were represented using sets of nonlinear tension-only connector elements as described in Campbell and Petrella (2015). The nonlinear ligament properties were based on exponential fits from the literature (Ayturk and Puttlitz, 2011; Nolte et al., 1990; Rohlmann et al., 2006).

The annulus fibrosis was modeled using the Holzapfel–Gasser–Ogden material formulation in Abaqus with 3108 linear hexagonal elements per disc. This material model allows a continuous hexagonal mesh to represent a NeoHookean ground matrix with fiber reinforcement. The continuous mesh is of particular importance using the automated methods because the shape and size of the disc elements change depending on the specimen geometry. The Holzapfel–Gasser–Ogden material model allows fiber angles to be defined numerically so that orientation of the fiber network is maintained irrespective of morphological changes in the continuum. Hybrid elements were used for the annulus fibrosis to allow incompressible behavior without shear locking (Eberlein et al., 2001, 2004). The annulus fibrosis matrix properties were derived from Eberlein et al. (2001, 2004). The annulus fibrosis properties were divided into anterior, lateral, and posterior regions (Rao, 2012). A different fiber stiffness was defined in each region (Eberlein et al., 2001, 2004; Malandrino et al., 2013) and the fiber angle was based on the average angle for each region in a regression model (Holzapfel et al., 2005). The generalized material parameters are summarized in Table 1.

The nucleus pulposus was modeled as a fluid cavity in Abaqus using 2154 quadrilateral reduced integration surface elements (SFM3D4R) per disc to define the nucleus boundary. The fluid cavity definition in Abaqus represented the nucleus pulposus with homogeneous fluid pressure. The cavity was defined with the bulk modulus of water based on the template model (Rao, 2012) and consistent with other fluid cavity models from the literature (Charles et al., 2013; Niemeyer et al., 2012). The facet cartilage was modeled using rigid hexagonal elements with 864 elements for each section of superior cartilage and 336 elements for each section of inferior cartilage. Rigid contact surfaces were created based on the geometry of each set of rigid cartilage elements. The facet contacts were defined using frictionless softened contact with a linear pressure-overclosure relationship to define interaction of the sets of rigid cartilage surfaces. The initial gap between the cartilage surfaces was defined relative to the subchondral bone as identified on the CT for each specimen (Campbell and Petrella, 2015). The ligament endpoints, superior, and inferior surfaces of the discs, and interior surface of the cartilage elements were all rigidly fixed to the bones where they attached.

2.2. Mesh convergence study

The mesh convergence study was performed to confirm adequate mesh density such that the key variables in our context of use were not influenced significantly by mesh density. The mesh was considered converged if the key output variables changed less than 5% when the mesh density was doubled. A single L4-L5 FSU from one arbitrarily chosen auto-generated FE model was used. Pure moment loads up to 10 Nm were applied to the model in each of the six primary bending modes (flexion, extension, left/right axial rotation, and left/right lateral bending). Rotation, disc pressure, and facet contact force were used as output variables.

2.3. Semi-direct validation study

The semi-direct validation study was conducted to evaluate the FE automation method by comparing simulation results to experimental measurements and results from a manually created FE model. The semi-direct validation comparison specifically assessed the ability of the automation algorithm to create a valid, properly configured subject-specific FE model. Material properties were obtained from a prior study (Rao, 2012) that calibrated an FE model to experimental tests on a lumbar spine with progressive sectioning of the ligaments. The experimental study reported torque rotation curves for each level of the L1-S1 lumbar spine in all six primary bending modes for both the experiment and calibrated model. In the current study, CT data for the same

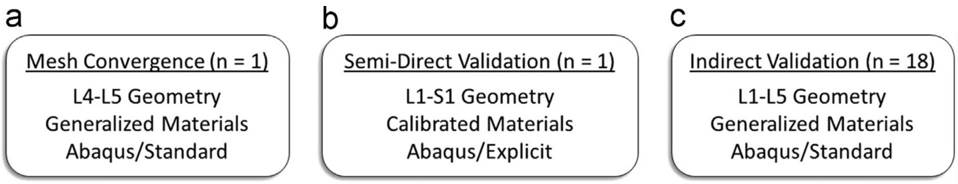

Fig. 1. The three modeling tasks used to support V&V of the automated lumbar spine FE modeling algorithm.

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