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Validation of a C2–C7 cervical spine finite element model using specimen-specific flexibility data

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ABSTRACT

This study presents a specimen-specific C2–C7 cervical spine finite element model that was developed using multiblock meshing techniques. The model was validated using in-house experimental flexibility data obtained from the cadaveric specimen used for mesh development. The C2–C7 specimen was subjected to pure continuous moments up to ±1.0 N m in flexion, extension, lateral bending, and axial rotation, and the motions at each level were obtained. Additionally, the specimen was divided into C2–C3, C4–C5, and C6–C7 functional spinal units (FSUs) which were tested in the intact state as well as after sequential removal of the interspinous, ligamentum flavum, and capsular ligaments. The finite element model was initially assigned baseline material properties based on the literature, but was calibrated using the experimental motion data which was obtained in-house, while utlizing the ranges of material property values as reported in the literature. The calibrated model provided good agreement with the nonlinear experimental loading curves, and can be used to further study the response of the cervical spine to various biomechanical investigations.

1. Introduction

Finite element modeling is critical to understanding the internal biomechanical response of the cervical spine to external stimuli. Clinical studies, *in vitro* experiments, and animal models have the ability to provide important information regarding cervical spine biomechanics in response to various treatments. However, these techniques are limited by their inability to predict the localized stress and strain fields within the spine itself. It is important that a finite element model accurately represents the desired structure of interest not only anatomically but also with regard to the material properties. Due to the time and effort required for subject-specific cervical spine model development, an 'average' geometry is often used. The cervical spine exhibits nonlinear behavior; nevertheless, it is common for cervical spine finite element models to be validated only via an end-point response to a particular load or moment [1–3].

Experimental cervical spine moment–rotation data in the literature vary widely due to specimen age, the number of segments tested, specimen orientation, the loading protocol, and biological variation. The combination of generalized geometry and averaged experimental data corridors from the literature dictate that a finite element model's behavior can span a fairly wide range and still be considered valid. In contrast, subject-specific validation is a desirable task because it increases the confidence in parameters predicted by a finite element model [4]. The ability to examine anatomical and degenerative differences between patients/subjects is important when considering treatment strategies and the design of spinal devices. Subject-specific validation studies rely on data obtained from the same specimen which was used to build the models. In most cases, these studies still rely on soft tissue material properties from the literature because obtaining these properties *in vitro* for every specimen is impractical, and currently not feasible *in vivo*. However, variability in experimental material property data can be used to calibrate a model to further enhance its ability to mimic subject-specific experimental behavior [5].

In this study, our goal was to further increase the confidence in our spine modeling techniques [6] by developing a specimen-specific C2–C7 finite element model and subjecting it to a rigorous validation process. As a starting point, material properties commonly reported in the literature were assigned as a baseline condition. This provided not only a basis for the model, but also insight as to the feasibility of these material assignments for a given model definition. The same specimen used for model development was experimentally tested and the entire loading response was

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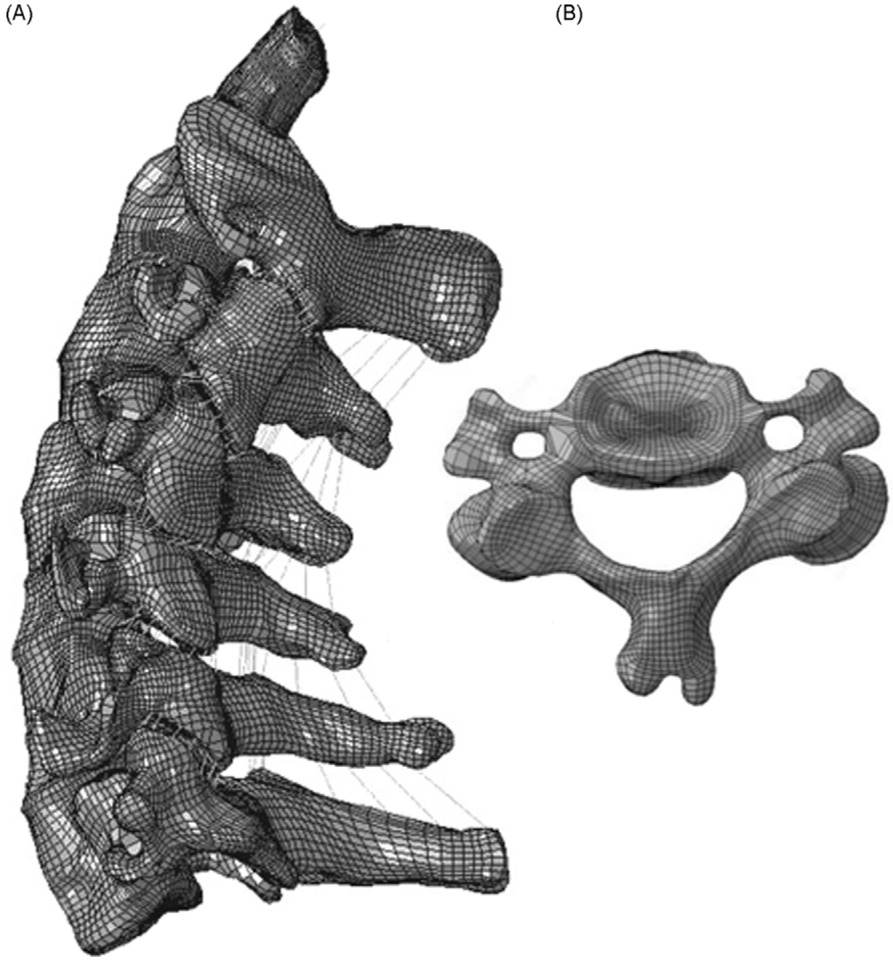

Fig. 1. (A) C2–C7 mesh with nearly 130,000 elements. (B) Axial view of a single vertebra.

compared to the computational modeling results (up to ±1.0 N m flexion–extension, lateral bending, and axial rotation).

2. Methods

2.1. Finite element model development

A detailed geometrically accurate C2–C7 finite element (FE) model was developed using our interactive multiblock meshing techniques [6] (Fig. 1). A CT image dataset from a cadaveric specimen (74 years of age) provided the foundation for the bony structures, while MR scans were used to approximate the boundaries of the intervertebral discs. In turn, these boundaries constituted the superior and inferior peripheral traces representing the vertebral body endplates. The reader is referred to Kallemeyn et al. [6] for a detailed description of the meshing techniques. The finite element software ABAQUS (Simulia, Providence, RI) was used to perform the analyses.

The intervertebral discs were modeled as a central nucleus surrounded by an annular ground substance reinforced by fibers acting at approximately ±25° from the transverse plane. The fibers were modeled using a rebar definition. The nucleus was modeled as an incompressible fluid whose volume was approximately 33% of the entire disc volume [4,7]. Five major cervical spine ligaments were incorporated into the model, including the anterior longitudinal (ALL), posterior longitudinal (PLL), ligamentum flavum (LF), interspinous (IS), and capsular ligaments (CL). The ligaments were defined as 3D truss elements acting nonlinearly in tension only via the hypoelastic material designation in ABAQUS, which allowed for the definition of axial stiffness as a function of axial strain [8–11]. The model was initially assigned material properties reported in the literature as common to the cervical spine (i.e., cortical and cancellous bone, intervertebral discs, and ligaments; Table 1) [12–19]. This model will be referred to as the 'baseline' model from this point on.

A rigid surface was created on the superior aspect of the C2 vertebral body for applying moments to the model. The nodes on the inferior surface of C7 were fixed during the analyses. The baseline C2–C7 model was evaluated in flexion–extension, lateral bending, and axial rotation to a maximum moment of ±1.0 N m so as to mimic the following experimental protocol.

2.2. Experimental testing protocol

2.2.1. Multilevel specimen

The cadaveric specimen used for model development was tested experimentally. The specimen was kept frozen at −20 °C until the day of testing. After thawing to room temperature, the cervical spine (C2–C7) was dissected and the soft tissue removed, with care taken to preserve the joint capsules, intervertebral discs, and ligaments. Several wood screws were drilled into the vertebral bodies of C2 and C7 (to improve interdigitation with the potting material); thereafter, these vertebrae were positioned in custom designed fixtures and potted in a polymer resin (Bondo^{TM}, 3M Corporation, St. Paul, MN). The specimen was positioned by visual inspection such that the C4–C5 disc had a horizontal orientation. Photographs