Uncertainty Quantification and Probabilistic Modeling of a Cervical Spine Motion Segment in Flexion, Extension, and Tension

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I. INTRODUCTION

Neck and spinal pain are often reported by military aircrew and it can negatively impact their health and functional capability [1]. While there is no consensus on the etiology of spinal pain in aircrew, mechanical loading is believed to be a driving factor in its development [2]. Finite element (FE) modeling can be used to understand tissue-level mechanics in the aviation loading environment. However, traditional FE models are limited by their failure to account for variability present in anatomical tissue material properties (i.e. most models use average properties). Therefore, results are not applicable to an entire population [3-4]. This limitation can be overcome using probabilistic methods that account for uncertainty and variability in simulated spinal structures, such as tissue properties. Thus, probabilistic methods can be used to estimate population-wide tissue-level mechanics in aircrew. As a preliminary step in modeling the entire cervical spine, this study implements a probabilistic approach to model a functional motion segment (FSU). Material properties are implemented as independent, random variables with regional literature-derived distributions and a variance-based global sensitivity analysis is used to identify which material properties drive variation in the model's response. Three motions are considered: Flexion, Extension, and Tension. For each motion, the model's response is compared to cervical spine FSUs experimental data using a quantitative error metric and a sensitivity analysis is performed [5].

II. METHODS

A baseline FE model of a cervical spine FSU was constructed in LS-DYNA at the level of the $4^{th}/5^{th}$ cervical vertebrate (C4/C5; Fig. 1) using Zygote 5.0 anatomy corresponding to a 50^{th} percentile male (height/weight). The FE model was loaded to simulate flexion, extension, and tension experiments performed on C4/C5 FSUs [6-7]. Specifically, 0–3.5 Nm (Flexion, Extension) and 0–300 N (Tension) was applied to a rigid cap on C4 in the sagittal plane, while the lower third of C5 was fixed. Relative rotation (Flexion, Extension) or displacement (Tension) of C4 with respect to C5 was used as the model response.

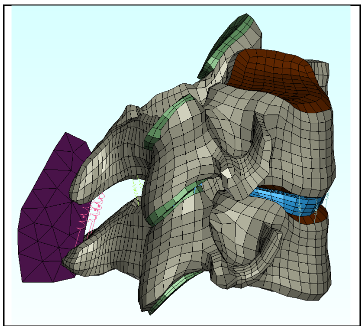

Fig. 1. FE model of the C4/C5 FSU. The model consists of two vertebrae (tan), their endplates (brown), an intervertebral disc (blue), facet cartilage (green), and six ligaments (purple shell + springs).

Uncertainty Quantification: to capture the uncertainty and variability within this system, 30 material properties were implemented as random variables with literature-derived distributions in the FE model. Endplates and cortical bone were represented as isotropic elasto-plastic shells with Young's Modulus and shell thicknesses implemented as independent random variables; yield stress was dependent on Young's Modulus [8-11]. Vertebral trabecular bone was modeled as an isotropic elasto-plastic solid with Young's Modulus and yield stress implemented as dependent random variables with a linear correlation of 0.79 [9]. Uncertainty and variability in the intervertebral disc (IVD) material properties were represented in three parts: annulus fibrosus matrix (compressible foam), annulus fibrosus fibers (fabric layers), and nucleus pulposus (isotropic hypoelastic solid). IVD fiber angle, matrix stiffness, and shear modulus were modeled as independent random variables [12-14]; fiber angle varied in six regions to replicate observed orientations [12]. The anterior longitudinal ligament, posterior longitudinal ligament, interspinous ligament, ligamentum flavum, and capsular ligament were represented as nonlinear springs with stiffness as independent random variables [15]. The nuchal ligament was represented as a simplified rubber with ligament stiffness modeled as an independent variable [15]. Facet joint cartilage was modeled as an isotropic hypoelastic solid with Young's Modulus as an independent random variable.

Probabilistic Analysis: a Monte Carlo-based probabilistic analysis was performed using a Gaussian-Process response surface (GP-RS) in place of the FE FSU model. The GP-RS allowed rapid probabilistic analysis (e.g. probabilistic FE model response, probabilistic error metric, and sensitivity factors) as large numbers of simulations are needed (> 100,000) with Monte Carlo sampling methods to accurately resolve small probabilities and risk

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values. One GP-RS was constructed for each simulated motion [16]. For each motion, 300 FE simulations, with material properties drawn from uniform distributions using Latin Hypercube sampling, were used to build the GP-RS using previously described methods [16-17]. Leave-one-out cross validation was used to assess GP-RS quality.

Two probablistic metrics were computed: an error metric (area metric) and variance-based global sensitivity factors. The area metric is the normalised area between the probabilistic model predicted and experimental cumulative distribution functions (CDFs). It quantifies the error between the simulated motion segment motion (i.e. response surface predictions) and experimental motion at selected response points; high values (expressed as a percentage) indicate discrepancies between the CDFs [3][5][18]. Response points were spaced at 0.5 Nm (Flexion, Extension) and 100 N (Tension) increments. At each response point, simulation CDFs were built by Monte Carlo sampling of the response surface with material properties drawn from literature-derived distributions [17]. Material properties were modeled as truncated normal distributions bounded at the literature minimum/maximum values, if reported, or ±3 standard deviations. If no standard deviation was reported, it was assumed to be 20% of the experimental mean. Experimental CDFs were modeled as lognormal distributions with experimental mean and standard deviation [6-7]. A global probabilistic sensitivity analysis was also performed in NESSUS 10.0 [17]; the generated global sensitivity factors (SFs) quantify how variability in the material properties (i.e. independent variables) contribute to the response variability and range from 0 to 1 [4][17].

VI. INITIAL FINDINGS

The predicted response corridors were narrower than those observed experimentally (Fig. 2). In Tension, the area metric at 100 N, 200 N, and 300 N of applied force was 13% each applied force. In Extension, the area metric at 0.5 Nm, 1.5 Nm, 2.5 Nm, and 3.5 Nm was 27%, 28%, 32% and 38%, respectively. In Flexion, the area metric at 0.5 Nm, 1.5 Nm, 2.5 Nm, and 3.5 Nm and was 48%, 23%, 14%, and 18%, respectively. For each motion, response surface cross validation R^2 was greater than 0.98.

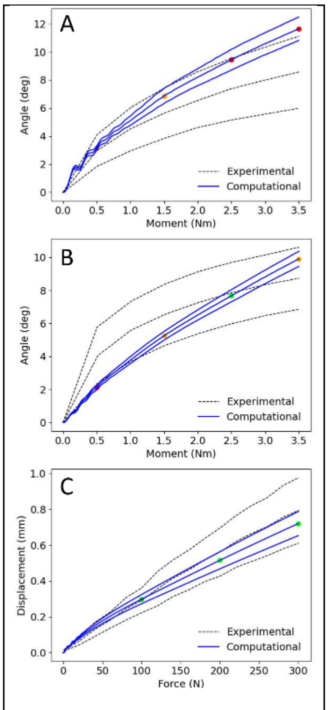

Fig. 2. Experimental (black dashed line) and simulated (blue solid line) response corridors in Extension (A), Flexion (B), and Tension (C). Area metric values at response points are shown by colored circles: green (<15%), orange (15–30%), red (>30%).

In Flexion, most response variation was due to the variation in the stiffness of the ligamentum flavum (SF = 0.26), the annulus fibrosus matrix (SF = 0.20), and the interspinous ligament (SF = 0.19). Remaining variation was attributed to stiffness of the trabecular bone (SF = 0.13), capsular ligament (SF = 0.07), and nuchal ligament (SF = 0.04). In Tension and Extension, the most response variation was due to variation in annulus fibrosus fiber angle (SF = 0.69 for Extension, 0.58 for Tension).

VI. DISCUSSION

This study demonstrates that probabilistic FE modeling can be used to predict distributions that represent observed biomechanical responses in the cervical spine. In Tension, the area metric indicated good agreement between the expected and simulated response distributions. In Extension and Flexion, the area metric indicated lower agreement at multiple response points. However, an advantage of this probabilistic methodology is that the SFs can be used to guide model improvement. For example, the SFs indicated ligament stiffnesses had a large effect on the Flexion response. As such, updating the ligament material model may improve model response. Similarly, the annulus fibrosus fiber angle had a large effect on the simulation response in Extension and Tension. In the FE simulation, fiber angle was varied circumferentially, but not radially (e.g. inside-to-outside); variations in both directions are observed experimentally, thus updating fiber angle to better replicate physiologic distributions may improve the simulation's response [12][19]. Other factors that were not included in the simulation as random variables, such as bone morphology (e.g. vertebral height, width), will have a significant effect on FSU motion and could be included to improve model performance [18].

VI. REFERENCES

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