Influence of Parameter Bounds on a Functional Spine Unit Model Under Traumatic Loading

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I. INTRODUCTION

The cervical spine is the most frequently injured region of the spine [1], and cervical spine ligaments are involved in the response to loading during events such as automobile collisions [2]. While variability of both cervical spine injury tolerance and ligament material properties have been reported, the relationship between the two is not well-known. Parametric analysis has been conducted to understand the role of ligament material properties on the functional spine unit (FSU) response, but representation of material property variability in the design of the analysis has not been well-studied. Two key considerations in the design of parametric analyses are the sampling method and the bounds representing the variation of the input parameters. In particular, the input parameters must be realistically bounded to efficiently and accurately quantify how material property variability contributes to variability in the predicted response of a model, in this case a motion segment. In parametric studies of FSU models, however, the relevance of the parameter bounds to experimental data and to the predicted range of model responses has not been well-documented. The aim of the current study was to identify representative bounds for the ligament material properties in an FSU finite element (FE) model [3] and to assess the effect of parameter bounding on the predicted outcome. Specifically, a method to define non-rectangular bounds for bivariate data is introduced, and an example of how parameter bounds can influence the predicted range of model responses is presented.

II. METHODS

A C4-C5 FSU FE model (Fig. 1A) was extracted from the Global Human Body Models Consortium (GHBMC) M50 model version 5.1. The C4 superior endplate was subject to an extension moment at a rate of 0.09 Nm/msec [3], and the vertebral rotation was calculated using a commercial explicit solver (LS-DYNA R9.2.0, Ansys, Livermore USA).

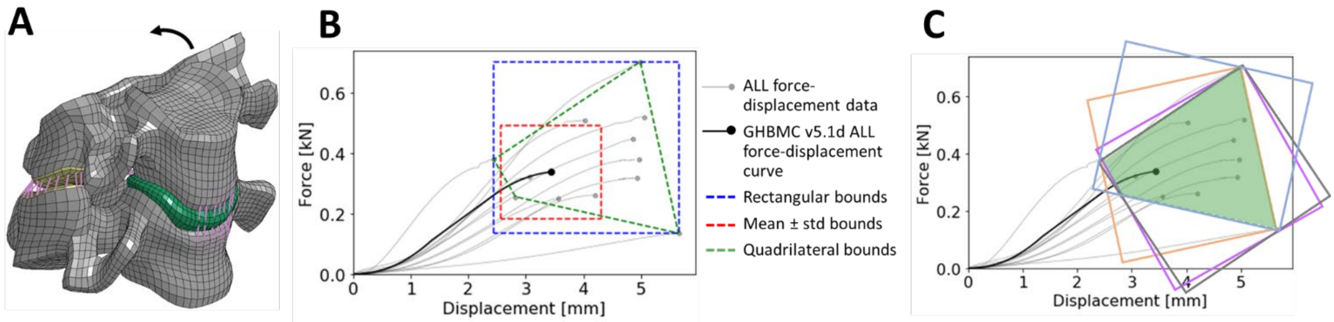

Fig. 1. (A) The GHBMC v5.1 C4-C5 model. (B) Experimental quasi-static force-displacement responses of anterior longitudinal ligaments (ALL); gray lines, with gray markers indicating failure forces and displacements; the ALL force-displacement curve in the GHBMC v5.1 model (black, with black marker indicating (d_{max}, F_{max})); and the three bounds imposed on (d_{max}, F_{max}) of the ALL. (C) Overlay of four possible bounding boxes (outlined in colour) shown over ALL force-displacement curve data. The intersection of the four boxes (green shaded region) was defined as the quadrilateral bounds.

The five major cervical ligaments (anterior longitudinal ligaments (ALL), posterior longitudinal ligaments, interspinous ligaments, capsular ligaments, ligamentum flavum) were modeled as 1D tension elements. The quasi-static force-displacement response of each ligament, derived from [4], reached a maximum force (F_{max}) equal to the mean experimental failure force reported. The corresponding displacement (d_{max}) was the mean experimental failure displacement. Ligament material properties were varied by scaling the force-displacement curves, which were confined by imposing bounds on d_{max} and F_{max}. For each of the five ligaments, three sets of bounds were computed (example for the ALL in Fig. 1B). The rectangular bounds (Fig. 1B, blue box) were defined such that d_{max} (and F_{max}) lay between the minimum and maximum experimental failure displacements (and

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forces). The mean ± std bounds (Fig. 1B, red box) were defined such that d_{max} (and F_{max}) were within one standard deviation of the mean experimental failure displacement (and force). Finally, to construct the quadrilateral bounds (Fig. 1B, green box), the experimental failure displacements and forces were plotted in (d, F)-space to construct a quadrilateral enclosing all data points. Pairs of (d_{max}, F_{max}) were constrained to remain within the quadrilateral. The quadrilateral was constructed (Fig. 1C) by first computing the set of arbitrarily oriented boxes bounding the experimental data in (d, F)-space (i.e. the set of oriented bounding boxes) by the rotating caliper method [5]. Then, the quadrilateral bound was defined as the intersection of four of the bounding boxes. If more than one combination of bounding boxes existed, the quadrilateral selected was the one with smallest mean distance between each vertex and the closest data point.

For each bounding method, the force-displacement curves of each ligament were varied by a four-level factorial design where the four levels corresponded to force-displacement curves with (d_{max}, F_{max}) coinciding with the vertices of the bounds in (d, F)-space. The FSU FE model moment and rotation at failure were compared to those reported in experiments [6] for extension loading.

III. INITIAL FINDINGS

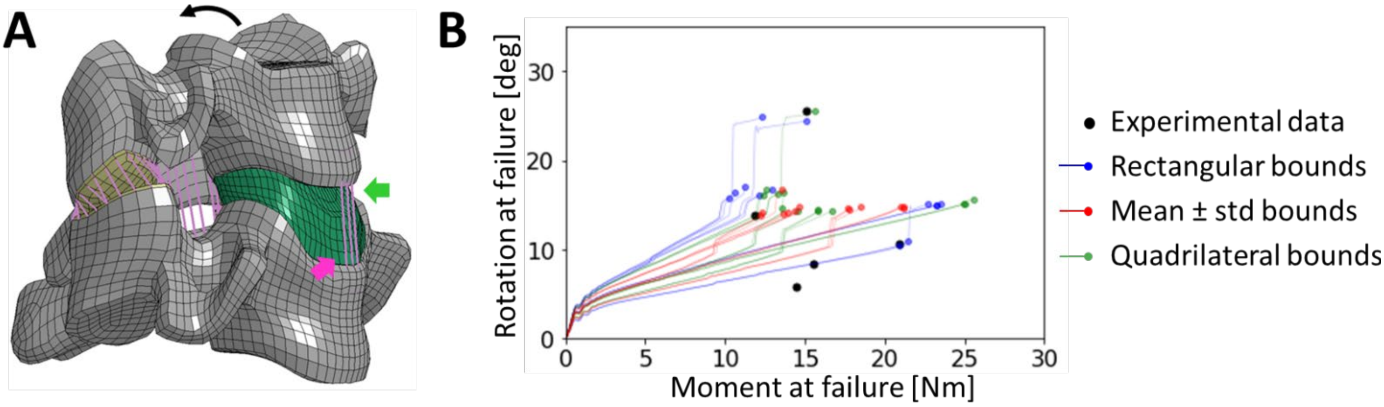

Fig. 2. (A) The C4-C5 model after ALL rupture (pink arrow) and disc avulsion (green arrow). (B) Failure moments and rotations of all simulations of the C4-C5 FSU model under extension (coloured markers, with lines indicating rotation-moment responses), plotted with the experimental data (black).

An extension moment applied to the FSU model led to tensile loading of the anterior intervertebral disc and ALL. Tissue failure progressed from ALL rupture to disc avulsion (Fig. 2A). The rotation at ultimate failure of the simulations (Fig. 2B) was within the range of the reported experimental data [6]. The predicted range of failure moments exceeded the experimental range when the rectangular bounds were used; was closest to the experimental range when the mean ± std bound was used; and exceeded only the upper bound of the experimental range when the quadrilateral bounds were used. Prior to ultimate failure, the timing and occurrence of ligament failure could vary according to the bounds applied. Among the simulations using the rectangular bounds, the applied moment at the initiation of ligament failure ranged from 5.2 Nm to 23 Nm, whereas the range was 9.2 Nm to 22 Nm with the mean ± std bounds and 12 Nm to 26 Nm with the quadrilateral bounds.

IV. DISCUSSION

The three-input parameter bounding methods investigated were associated with different ranges of failure moments and rotations relative to the experimental range. The example comparison of the three bounds in Fig. 1B demonstrates how each bound can differently represent the variation in experimental data. The rectangular bounds, while enclosing all the data, may overestimate the region occupied by the data, while the mean ± std bounds may be overly conservative: eight of the 12 experimental samples lay outside the bounds. The quadrilateral bounds also enclose all the data, but cover a smaller area than the rectangular bounds. As a result, samples drawn with the quadrilateral bounds are more likely to lie within the boundaries of the available data. The quadrilateral bounds may, then, more reliably facilitate the sampling of parameter values that are representative of the available data. Given the potential for the bounds used to influence the responses observed, the selection of parameter bounds that are representative of experimental data will be necessary to accurately quantify how variability of ligament material properties can contribute to variability of the predicted FSU response.

V. References

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