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Research Paper

# Thoracic response targets for a computational model: A hierarchical approach to assess the biofidelity of a 50th-percentile occupant male finite element model

*David Poulard*[a,*], *Richard W. Kent*[a], *Matthew Kindig*[b], *Zuoping Li*[a], *Damien Subit*[a]

[a]*Center for Applied Biomechanics, University of Virginia, Charlottesville, VA, USA*
[b]*RR&D Center of Excellence for Limb Loss Prevention and Prosthetics Engineering, Department of Veterans Affairs Puget Sound Health Care System, Seattle, WA, USA*

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ABSTRACT

Current finite element human thoracic models are typically evaluated against a limited set of loading conditions; this is believed to limit their capability to predict accurate responses. In this study, a 50th-percentile male finite element model (GHBMC v4.1) was assessed under various loading environments (antero-posterior rib bending, point loading of the denuded ribcage, omnidirectional pendulum impact and table top) through a correlation metric tool (CORA) based on linearly independent signals. The load cases were simulated with the GHBMC model and response corridors were developed from published experimental data. The model was found to be in close agreement with the experimental data both qualitatively and quantitatively (CORA ratings above 0.75) and the response of the thorax was overall deemed biofidelic. This study also provides relevant corridors and an objective rating framework that can be used for future evaluation of thoracic models.
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## 1. Introduction

Thoracic injuries are the most common blunt trauma sustained by restrained occupants in motor vehicle crashes (Carroll et al., 2009). Among thoracic injuries, rib fractures are commonly used as an indicator of a crash severity, as these fractures are relatively straight forward to detect in a cadaveric model and an increase in the number of rib fractures was shown to be associated to an increase of the risk of sustaining more severe injuries to the internal organs (aorta, lungs, heart) (Carroll et al., 2009). Thoracic modeling is complicated by its geometry and material heterogeneity, as it consists of the ribcage, the viscera, the musculature and the skin, and its overall mechanical response results from the contribution of these soft and hard tissues. Understanding how

*Correspondence to: University of Virginia Center for Applied Biomechanics, 4040 Lewis and Clark Drive, Charlottesville, VA 22911, USA. Tel.: +1 434 2967288x117; fax: +1 434 2963453.
E-mail address: dp5fv@virginia.edu (D. Poulard).

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the thorax deforms under dynamic loading applied by improved restraint systems to vehicle occupants is an active area of research.

Finite element (FE) models of the human thorax or the entire body have been developed to investigate the structural response of the thorax in vehicle crashes and to establish its injury tolerance (Robin, 2001; Iwamoto et al., 2002; Ruan et al., 2003; Kimpara et al., 2005; Zhao and Narwani, 2005; Song et al., 2009; Ito et al., 2009; Vezin and Berthet, 2009). The biofidelity of the majority of the existing thorax models have been typically evaluated against frontal pendulum impacts (Kroell and Schneider, 1971) and lateral impacts (Lau and Viano, 1988; Shaw et al., 2006) by comparing the global responses of the FE model to the experimental responses of various post-mortem human surrogates (PMHS) at a given impact velocity. Corridors are formed by bounding the individual response, typically described by the applied force and chest compression time histories.

The antero-posterior deflection of the chest is commonly used as a metric to estimate the risk of rib fractures as the former was shown to correlate with the later (Kent and Patrie, 2004). While using chest deflection as a proxy for rib fractures is a reasonable approach for comparing models to the response of anthropometric test devices (crash test dummies), it is not sufficient to fully characterize the injury response of the thorax. In particular, FE models have the capabilities to mimic the load distribution through the thorax and provide researchers and engineers with detailed information about the injury mechanisms. To do so however, the model responses at the sub-structural levels (e.g. rib segment and ribcage) have also to be evaluated, as good biofidelity scores for the global response does not imply that the model can be used to estimate mechanical parameters at a smaller scale (such as strain in the ribs). Furthermore, additional validation of the thorax model at a hierarchical sub-structural level would help determine the correct global model responses in a way that minimizes tuning of the model material properties to match the experimental data.

Recently, a study showed the feasibility of using an objective rating tool called CORA (CORelation and Analysis, Partnership for Dummy Technology and Biomechanics, Gehre et al., 2009) for the evaluation of full body FE models (Vavalle et al., 2013). It is likely that a quantitative assessment tool such as CORA would be useful to evaluate the model response of a thorax computational model at different structural levels.

The goal of the current study was twofold:

- reviewing experimental data and generating response targets for a quantitative assessment of the thorax
- evaluating the performance of the thorax of a recent finite element model for selected loading conditions.

## 2. Materials and methods

### 2.1. *Finite element body models overview*

The finite element body model (FBM) used in this study was the version v4.1 of the seated 50th-percentile male, developed in the LS-DYNA solver for the Global Human Body Models Consortium (GHBMC). This model was developed based on geometrical surface generated from medical images (Gayzik et al., 2009). An interactive multi-block meshing approach was used to generate high quality quadrilateral and hexahedral meshes of the thorax anatomical structures (Li et al., 2010a, 2010b). Second, a methodology based on the mesh blocks was developed to assign cortical thickness data taken from a micro-CT study to each of the nodes in the cortical shell elements of the ribs along the longitudinal direction and around the cross-sectional perimeter (Li et al., 2010c).

Cortical and trabecular bone behaviors for the rib, sternum, scapula, clavicles, humerus, radius and ulna were simulated using an elastic–plastic material model with strain-rate effect scaling of the yield stress (*MAT_24 in LS-DYNA material library). Rib fracture was defined by setting an ultimate plastic strain of cortical and trabecular components to 1.8% and 13% respectively representing a 50 years old occupant (Golman et al., 2014). The thoracic vertebrae were modeled as rigid bodies (*MAT_20). Young moduli derived from Zhao and Narwani (2005) were used for the contact definition between adjacent vertebrae. Although the vertebrae are rigid bodies, the definition of the Young modulus is required to solve the contact equations by the penalty method. The intervertebral disks are modeled using kinematic spherical joints with stiffness based on the data in Panjabi et al. (1976). The costo-vertebral spherical joint stiffness was taken from the values measured by Duprey et al. (2010). Heart and lung organs were modeled by the heart and lung tissue models in LS-DYNA (*MAT_128 and *MAT_129). The following model components were all assumed to be linear elastic materials: the inter-costal muscle, costal cartilage, diaphragm and blood. This full model was described previously (Li et al., 2010a, 2010b) and its development was determined using several parametric analyses (Kindig et al., 2013).

### 2.2. *Evaluation cases*

This section presents an overview of the experimental tests and the corresponding simulation approach. These experimental cases were selected based on their relevance, the compatibility of the available data with the CORA approach, and the large range of structural levels they cover.

#### 2.2.1. *Rib segment anterior–posterior bending*

First, the rib segment models were evaluated against data from anterior–posterior bending tests (Kindig, 2009). In this study, a total of 94 rib specimens from nine subjects (seven males and two females) were extracted from rib levels 2 through 10. Each rib segment was loaded by displacing the anterior extremity of the rib towards its posterior extremity in the loading plane. A single rotational degree of freedom was permitted at each extremity, which rotated about the axis normal to the loading plane. A dynamic displacement rate of 0.5 m/s was used to load the ribs to failure. Each rib segment model was individually created and simulated in anterior–posterior bending, using the same boundary conditions as those in the experiment (Fig. 1). The shell elements within approximately 7–10 mm of the anterior extremity and 15–20 mm of the posterior extremity were modeled as separate rigid-body components to reproduce the effect of the potting used in the experiments.

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