Computers in Biology and Medicine 99 (2018) 191–200

Contents lists available at ScienceDirect

Computers in Biology and Medicine

journal homepage: www.elsevier.com/locate/compbiomed

Modeling and validation of a detailed FE viscoelastic lumbar spine model for vehicle occupant dummies

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ARTICLE INFO

Keywords:
Finite element (FE) model
Lumbar spine
Viscoelastic discs
Modified HYBRID III dummy
Vehicle accident

ABSTRACT

The dummies currently used for predicting vehicle occupant response during frontal crashes or whole-body vibration provide insufficient information about spinal loads. Although they aptly approximate upper-body rotations in different loading scenarios, they overlook spinal loads, which are crucial to injury assessment. This paper aims to develop a modified dummy finite element (FE) model with a detailed viscoelastic lumbar spine. This model has been developed and validated against in-vitro and in-silico data under different loading conditions, and its predicted ranges of motion (RoM) and intradiscal pressure (IDP) maintain close correspondence with the in-vitro data. The dominant frequency of the model was f = 8.92 Hz, which was close to previous results. In the relaxation test, a force reduction of up to 21% was obtained, showing high agreement in force relaxation during the in-vitro test. The FE lumbar spine model was placed in the HYBRID III test dummy and aligned in a seated position based on available MRI data. Under two impulsive acceleration loadings in flexion and lateral directions with a peak acceleration of 60 m/s^2, flexion responses of the modified and original dummies were close (RoMs of 29.1° and 29.6°, respectively), though not in lateral bending (RoMs of 34.1° and 15.6°, respectively), where the modified dummy was more flexible than the original. By reconstructing a real frontal crash, it was found that the modified dummy provided a 10% reduction in the Head Injury Criterion (HIC). Other than the more realistic behavior of this modified dummy, its capability of approximating lumbar loads and risk of lumbar spine injuries in vehicle crashes or whole-body vibration is of great importance.

1. Introduction

In the recent years, dramatic increase in the usage of ground vehicles has raised the occupant safety concerns among scholars. Vehicle safety institutes chiefly place their utmost concentration on the frontal impact crashworthiness and occupant safety. Different crash test dummies are currently in use to assess the occupant safety of the ground vehicles in different crash scenarios. However, current widely-used crash dummies do not provide sufficiently instructive information of the lumbar spine injuries. HYBRID III 50th percentile male dummy is one of the most used crash test dummies in crashworthiness tests. HYBRID III is the first human-like crash test dummy which is the most widely used vehicle occupant dummy in the frontal crashes since 1990s [1]. The HYBRID III is an instrumented mechanical test device which mechanically represents human body response during frontal crash tests. The HYBRID III dummy has experienced evolutions over the years and enhanced in terms of bio-fidelity. Noureddine et al. [2] developed HYBRID III finite element (FE) model for crash simulations and validated the model against the experimental data. Lumbar spine component of the HYBRID III is a simplified structure; a bent molded cylinder strengthened by two metallic cables that are parallel with the main axis of the cylinder.

Evidences indicating the deficiencies of the dummies in crash tests have been discussed by Rao et al. in Ref. [3]. By evaluating the lumbar spine injuries among the occupants of Crash Injury Research and Engineering Network (CIREN)'s crashes, it was found that 13% of vehicle occupants sustained major and minor injuries in thoracic and lumbar regions. However, results of the crash tests did not report such spinal injuries in the occupants.

One of the most important features of a precise biodynamic modeling of spine for the purpose of vehicle crash is the time-dependent behavior of the soft tissues. According to the NHTSA (National Highway Traffic Safety Administration) vehicle crash test database [4], a typical frontal collision with a barrier with a closing speed of 56 km/h exerts an acceleration on the occupant with a magnitude of ~200 m/s^2 in only 100 ms. Order of magnitude of the loads and the loading rates in such a typical crash are very high that makes the time a prominent factor. Consequently, an accurate spinal response should be provided by means

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https://doi.org/10.1016/j.compbiomed.2018.06.013
Received 21 May 2018; Received in revised form 13 June 2018; Accepted 14 June 2018

of viscoelastic property, particularly for soft tissues such as intervertebral disc (IVD) which exhibit time-dependent behavior. Equally important feature of an accurate biodynamic modeling is the level of the details elaborated on the model. Spine, as an intricate part of human body axial skeleton, consists of several components while overlooking each component may lead to an inaccurate modeling. To deal with the problems associated with the lumbar spine of the test dummies, the most reasonable approach will be a substitute for the lumbar component.

A study investigating the viscoelastic shear response in cadaver and the lumbar spine of the HYBRID III dummy showed discrepancies between the results in terms of initial stiffness and hysteresis effects [5]; it was predictable due to the time-dependent behavior of the IVDs. Similarly, comparison of cadaveric and dummy's lumbar has been made by Demetropoulos et al. [6]. During the test, dummy experienced loadings in the all possible degrees of freedom except axial rotation which left the evaluation of mechanical properties of the dummy's lumbar spine unclear. Additionally, it was found that in contrast to cadaveric lumbar spine, HYBRID III lumbar spine was stiffer in posterior shear than in anterior shear [6]. Danelson et al. compared the human body finite element model and HYBRID III dummy and found different results in viscous criteria, acceleration and displacement metrics [7]. Human body model used by Danelson et al. [7] neglected the lumbar spine injury and its undeniable effect on the occupant's behavior. In a previous research, Paul C. Ivancic employed a cadaveric lumbar segment composed of L3-L5 into an impact dummy with the purpose of examining the thoracolumbar spine injury in a falling from height incident; the results realistically reproduced the biodynamics of real-life falling by showing injuries to the L4 vertebra [8].

In order to address the problem associated with the test dummies, this work intended to propose a modified HYBRID III dummy FE model, promoted by a detailed lumbar spine FE model. Based on the 50th percentile healthy males mean dimensions [9–11], a detailed FE model of lumbar spine (L1-S1) was developed and validated. Validation of the model was done under static and dynamic loading conditions. Moreover, a frequency response analysis was conducted to examine its dynamic behavior. The lumbar components of the HYBRID III dummy were replaced by the detailed FE model according to the MRI images of seated occupants on a standard vehicle seat. Ultimately, an actual full-width frontal crash test was reconstructed to differentiate the response of the modified and original HYBRID III dummies.

2. Methods and materials

The passive ligamentous detailed FE model of the lumbar spine included L1-S1 vertebrae and the corresponding IVDs and ligaments. The model was developed based on the geometry and material properties reported in the literature and comprehensively validated against the available *in-vitro* and *in-silico* data. This FE model replaced the lumbar component of the HYBRID III FE model. The advantage of the modified HYBRID III dummy model is that it represents more realistic behavior of the lumbar region and provides interesting responses such as intradiscal pressure (IDP), intervertebral rotations (IVR) and spine failures during the related applications of the dummy tests such as vehicle crash and vibrations. All Finite Element simulations in this study were performed using LS-DYNA® (Livermore Software Technology Corporation, Livermore, CA, USA).

2.1. FE Modeling of the detailed lumbar spine

Endplates were the first components to be constructed based on the 50th percentile healthy males from the mean dimensions in Refs. [9–11]. The IVDs were created between the adjacent endplates. Pedicles and posterior elements of the vertebrae were simplified to resemble the geometry used by Niemeyer et al. [10]. Details of the FE model are illustrated in Fig. 1 and summarized in Table 1.

2.1.1. Endplate modeling

Geometrical modeling of the spine started with constructing the endplates at each level which meshed with 4-node shell elements of 1 mm uniform thickness. Dimensions and cross-section area of the endplates of all levels are shown in Fig. 1a. D_1 and D_2 are the major and minor diameters taken from Niemeyer et al. [10]. Elastic material properties with $E = 24$ MPa and $\upsilon = 0.4$ were assigned to the endplates according to the data by Naserkhaki et al. [12].

2.1.2. IVD modeling

IVDs were created by extruding the hexahedral elements between the adjacent endplates in 12 layers (Fig. 1a). IVDs comprised of nucleus pulpous and annulus fibrosus with the cross-section area proportions of 45% and 55%, respectively, based on the histological studies [13]. The annulus matrix was reinforced by distinct lamellae of collagen fiber networks. Eight crisscrossed lamellae of fibers oriented at ± 35° [14] strengthened the annulus matrix while their mechanical properties softened from outer to inner lamellae (Fig. 1a). The stress-strain curves presented by Schmidt et al. [14] were used to define the uniaxial tension-only strength of the collagen fibers. The elements to simulate such feature were discrete cable elements.

To model a time-dependent response, it was important to use viscoelastic material properties for the IVDs. Although hyper-elastic materials are able to simulate non-linear behavior of IVDs under static loadings [14–17], they are not an appropriate choice in dynamic loading conditions. Most popular material models for the time-dependent behavior of IVDs are monophasic and biphasic models [18]. Monophasic models are computationally more efficient and can provide the most important features needed for vehicle crash test dummies compared to the biphasic models, since the insidious permeation of liquid in the biphasic models is not a concern when it comes to the sudden loading of a vehicle crash [19,20]. Among different approaches of viscoelastic modeling, quasi-linear viscoelastic model which was first elaborated by Fung [21] has been proved to be of apt application in the mechanical modeling of soft-tissues, including human IVD.

Time-dependent properties of nucleus and annulus were modeled using modified quasi-linear viscoelastic material introduced by Fung [21]. Assuming that the nucleus is incompressible, one-dimensional expression of σ produces the uniaxial stress-strain curve and an extra viscoelastic term; thus, in the absence of viscose stress, the formulation relaxes to hyperelastic stress in the new formulation as follows:

$$\sigma(\varepsilon, t) = \sigma_\varepsilon(\varepsilon) + \sigma_V(t) \tag{1}$$

$$\sigma_V(t) = \int_0^t G(t-\tau)\frac{\partial\varepsilon}{\partial\tau}d\tau \tag{2}$$

$$\sigma_\varepsilon(\varepsilon) = \sum_{i=1}^{k} C_i\varepsilon_i \tag{3}$$

$$G(t) = \sum_{i=1}^{n} G_i e^{-\frac{t}{\tau_i}} \tag{4}$$

Where G is the shear modulus of Prony series and C_i are the coefficients of instantaneous elastic response. Time constants were obtained from Wang et al. [22] and shear and elastic responses were adjusted to the new formulation. Mechanical properties of the IVDs are summarized in Table 2.

Range of the time constants in Table 2 indicates the capability to evaluate the spinal response in frontal crashes of different initial diurnal disc dehydration conditions as discussed by Karakida et al. [23]. Thus, depending on the initial hydration condition of the IVDs, time constants will be different. For instance, according to Table 2, an IVD dehydration state which is equivalent to 3.45 s creep, requires the annulus and nucleus coefficients (G, C and τ) starting from the second and third terms, respectively. However, in this study, IVDs have been assumed to have