Fluid Structural Interaction Studies of Cervical Disc for Whiplash Loading

Pugazhenthi Kalaimani S, Davidson Jebaseelan D, Yuvaraj Purushothaman , Sivakumar Ramasami, Yoganandan Narayan

I. INTRODUCTION

The intervertebral disc is a major structural component of the human vertebral column. Along with the bilateral facet joints, it is responsible for controlled motions and stability of the spine. The major components of the discs are the nucleus surrounded by the annulus, which is confined between the two longitudinal ligaments that attach to the vertebral bodies on the anterior and posterior regions. Under whiplash loading the disc sustains the segmental loading via deformations of both the annulus and nucleus components. The presence of the water and proteoglycan in the disc [1] play a role in the mechanism of load transfer within and between the spinal joints, and this is true under static loads and impact loading conditions, such as rear impact. Most of the previous finite element modeling (FE) studies has modelled the human intervertebral disc based on the solid viscoelastic model (SVM) material formulation, and this is for computational simplification purposes. Fluid structural interaction (FSI) is an advanced mathematical modeling technique that captures the biophysics of the disc. The objective of this study is to model the disc using the FSI method and compare the responses with the traditional SVM disc models and demonstrate its improved disc response under rear-impact loading.

II. METHODS

The head-neck FE model used in the study simulated the vertebra of the body, posterior elements, intervertebral disc and ligaments. Each single vertebral body consisted of a thin cortical shell, a softer cancellous bone, endplate, and a posterior bony structure. The cortical bone was modelled as a linear isotropic material of 0.5 mm thick shell surrounding the cancellous bone and a 0.2 mm thick endplate was placed on the superior and inferior surface of the intervertebral disc. Each single motion segment of the FE model consists of vertebral bodies, intervertebral disc and five major vertebral ligaments. The intervertebral disc was modeled as being composed of the nucleus pulposus, annulus ground substance and annulus fibrosus (Fig. 1). Material properties from literature were used as definitions in the model [1,4]. The disc in the original model was considered as a solid viscoelastic material. It was then altered to include the fluid-structure behaviour, as follows.

The Gruneisen equation of state was included with the standard fluid material inside the nucleus and annulus ground with arbitrary Lagrangian-Eulerian multi-material models, to determine biomechanical response of disc under complex under rear impact. The loading condition was obtained from a previous study, in which human cadaver head-neck complexes were exposed to posterior-anterior acceleration at the base of the neck, i.e., at the T1 level [2]. The input velocity was 2.6 m/s, Figure 2 show the model and the applied pulse.

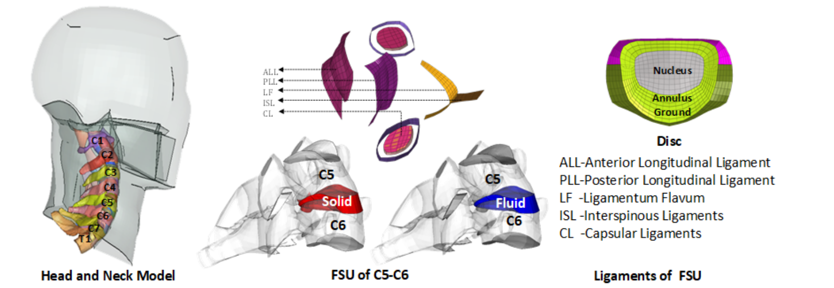

Fig. 1 Head and Neck FE Model, SVM(red), FSI (blue) Disc model with details of ligaments

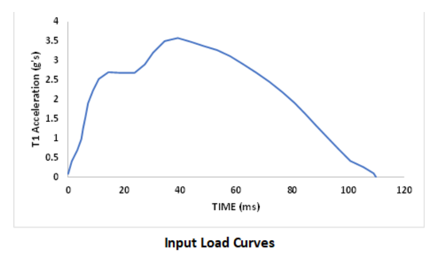

Fig. 2 Input mini-sled acceleration for 2.6m/s [2]

S. Kalaimani Pugazhenthi is a PhD Scholar SMEC and D. Davidson Jebaseelan (e-mail: davidson.jd@vit.ac.in; tel: 9790701475) and Ramasami. Sivakumar are Professors at Vellore Institute of Technology, Chennai Campus, India., Purushothaman. Yuvaraj is Research Scientist, Medical College of Wisconsin,USA and Narayan. Yoganandan is Professor of Neurosurgery in the Department of Neurosurgery at the Medical College of Wisconsin, USA.

III. INITIAL FINDINGS

Figure .3 shows the experimental corridor of the range of motion at the C5-C6 level and compares the output from the SVM and FSI disc models [1]. Responses from both models are within the validation corridor. However, differences in the pressure and volume were observed between the SVM and FSI models: SVM modelling approach produced linear responses, while nonlinear responses for both parameters at nucleus and annulus at each time-step were apparent with the FSI formulation. The quick response in the FSI, due to the continuum behaviour difference in solid and liquid interaction phase, was captured by this modelling formulation. Difference in change of shape inside the disc was observed with the FSI. The pressure and volume expansion and compression act majorly in the FSI, indicating its sensitivity to capture minor kinematic changes in the disc.

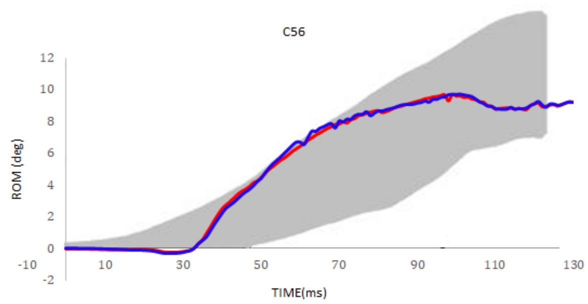

Fig. 3 The range of motion corridor from experimental data at the C5-C6 spinal level and comparison of the SVM (red) and FSI (blue) responses from the FE model showing similar validations of both models

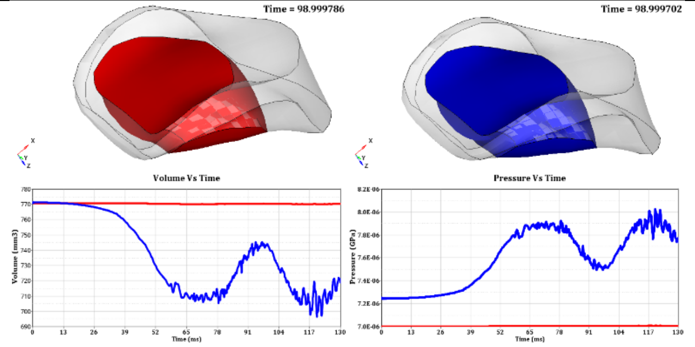

Fig. 4 Change in volume (left) and pressure (right) from the SVM (red) and FSI (blue) FE models. Data shown at the C5-C6 level. Note the nonlinear responses in both parameters from the FSI while the SVM response is flat. FSI is closer to the expected biological material response

IV. DISCUSSION

This study simulated the human intervertebral disc as a fluid-structure model and compared the responses with the traditional viscoelastic representation, which is used in the majority of modeling studies. As the model included both the fluid and structural components, it better mimicked the normal anatomical constituents of the disc. In principle, the response that accounts for both the fluid and the solid structures should be considered as more realistic and should differ from the pure solid viscoelastic response. This was shown to be true in the present study with the use of a previously developed FE model that used the traditional viscoelastic assumption for the disc. The pressure and volume responses were both nonlinear with the FDI model (Fig. 4). As the loading mimicked the whiplash acceleration input [3], these observations are applicable to this loading mode; however, other load vectors can be applied as the FSI formulation is mode invariant. Another key observation is that the range of motion does not depend on the formulation, i.e., SVM and FSI results in essentially the same response (Fig. 3), implying that for the overall segmental response, the disc material formulation type is secondary. However, to better understand the biophysics of the disc, FSI formulation is needed. As magnetic resonance imaging (MRI) is more routinely done in a clinical setting, and MRIs better define the disc, pressure-volume maps from FSI formulation may assist in correlating disc imaging to potential spinal disc-related disorders. The higher biofidelity offered by the FSI disc modeling approach has potential in clinical and bioengineering applications in whiplash scenarios. A full-blown study, with all the disc pressure-volume patterns, at different loading severities and for male and female anthropometries and perhaps with patient-specific models, is needed to fully understand the disc biophysics, and these studies are in progress.

V. REFERENCES

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