Sagittal Curvature and Vertebra Axial Geometry Effects on Cervical Spine Global and Local Responses

Jobin D. John, Narayan Yoganandan, Mike W. J. Arun, Gurunathan Saravana Kumar

I. INTRODUCTION

Studies have been conducted to determine the external and internal responses of the human cervical spine for medical, automotive, and military environments [1]. Experiments have been done to determine the external responses such as the range of motion (ROM), a parameter extensively used in clinical and finite element (FE) modelling research. Computational models have acted as an adjunct by providing information on the internal responses such as ligament strains [2-4]. While it is known that the human neck structures have inherent gender bias from biomechanical and anatomical perspectives, contributions of the various parameters of this complex continuum are not fully understood [5-6]. It is important to delineate the effects of individual parameters to better describe the response and correlate with known epidemiological and clinical studies to assist in the design, evaluation, and or recommendations of injury mitigating devices/systems in the stated environments. Consequently, the purpose of this study is to use an anatomically accurate model of the lower cervical segment to determine effects of spine curvature and vertebral geometry on the range of motion, anterior and posterior ligament strains, and zygaphophyseal joint compressions from inertial accelerations.

II. METHODS

An anatomically accurate FE model of the C5-C6 spine was developed using novel methods. Mapping blocks were used to capture morphological features of articular processes, pedicles, laminae, and spinous, transverse, and uncinate processes of human cervical vertebrae. Their geometries were obtained from CT scans. Intervertebral mapping blocks were spatially aligned based on disk geometry. The disk annulus and nucleus, bilateral zygaphophyseal joints with articular cartilage, capsular ligaments and synovial fluid, two longitudinal ligaments, ligamentum flavum, and interspinous ligaments were defined. The objects of the total parameterised model were the overall and component variations obtained from medical literatures: disk and zygaphophyseal heights and their inclinations in the sagittal plane, vertebra geometry including lengths of body and articular processes in the axial plane individually and in combination, length of laminae and spinous processes in the axial plane, overall spine size, and normal lordosis, straight, and kyphotic sagittal curvatures. The material properties of the elements were obtained from literature. The initial model was validated with in-house experimental ROMs [7]. The effects of sagittal curvature and vertebral geometry (vertebral body and facet lengths in the axial plane) were analyzed by applying segmental force and moment loads from rear impact at 9.3 km/h. The ROM, anterior longitudinal (AL) and capsular (anterior region, CL) ligament strains, and zygaphophyseal joint compression in the dorsal region (JC) were extracted from various FE models. The ANSA 16.1.0 was used to generate all models and LS-DYNA R8.1.0 was used to solve the nonlinear model. Correlations between output parameters, and curvatures and lengths of vertebrae in the axial plane were expressed using the Pearson coefficient.

III. INITIAL FINDINGS

The FE models representing the three curvatures are shown (Fig. 1a, b, c). The mapping block-based mesh generation technique for hard and soft tissues ensured common nodal connectivity between the three joints and vertebral components. The meshing technique eliminated the need for contact definitions, thus reducing non-linearity and improving model stability. All models developed using the mapping block-based meshing technique did not require re-meshing. The mesh quality in the models was excellent: >95% of elements with a Jacobian value of > 0.5 and 1.8% of elements with aspect ratios of > 5. The flexion-extension ROM was lower in the straighter than lordotic curvatures. Correlations between the specific output response and the input

JD. John is a PhD student in the Dept. of Eng. Design, Indian Institute of Technology Madras (IITM), Chennai, India, (jdaniel@mcw.edu). N. Yoganandan, Professor (corresponding author, tel 414-384-3453, yoga@mcw.edu), and MWJ. Arun, Assistant Professor at the Medical College of Wisconsin, Milwaukee, Wisconsin, USA, G. Saravanakumar, is Associate Professor, Depart. of Eng. Design, IITM, Chennai, India.

variables, expressed as sagittal curvature and vertebral axial geometry, are shown (Fig. 1 d).

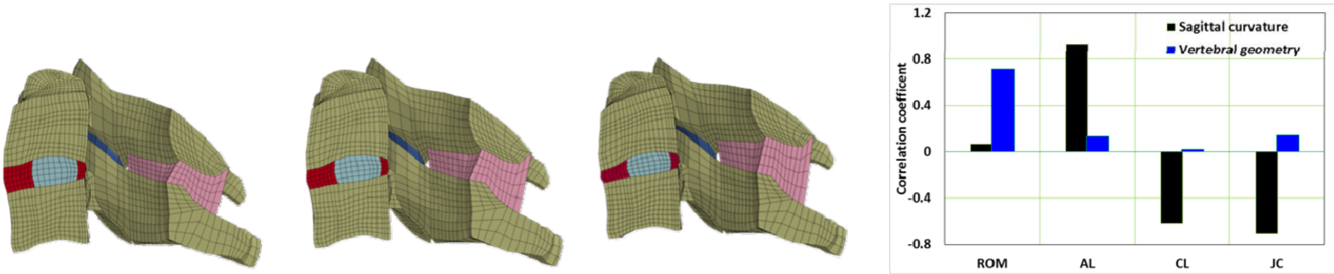

Fig. 1: Meshes of morphed C5-C6 spines representing lordotic (left, a), straight (2nd from left, b) and kyphotic (3rd from left, c) curvatures. The asymmetric placement of the intervertebral nucleus (blue) and annuls (red) and zygapophyseal anatomy are shown (dark blue). All models (not all shown) for variations of all parameters were developed by mapping block morphing technique and no re-meshing. Right (d) shows correlation data.

IV. DISCUSSION

Females are more vulnerable to injury in rear impact loadings [1][3]. Their spines are more flexible [1][2]. Factors such as reduced size (depicted by the vertebral geometry parameter) clearly showed increased ROM, i.e., enhanced flexibility, and it was overriding compared to the curvature. Increased ROM leads to lower loads on the spine, thereby increasing the demand on muscles to respond to the same level of input acceleration. The already decreased vertebral geometry and mass in females thus influence both the spinal column and muscle components [6][8]. The sagittal curvature, on the other hand, enhances anterior ligament strains, placing more demand on the anterior disk annulus. This may explain the hyperextension injury mechanism [9]. In addition, the curvature parameter adversely influences the capsular ligament strains and zygaphophyseal joint compression in the dorsal region, and further accentuates the local extension of the posterior column. Thus, the curvature affects both anterior and posterior columns while the size/vertebral geometry increases only the overall flexibility. The novel features of this study are (a) the incorporation of the more clinical relevant anatomy, i.e., eccentric placement of the disk and the multilayers of the annulus fibers, (b) use of the mapping block-based mesh generation technique, (c) comparative evaluation of spinal curvatures achieved by parametrising disk geometries, and (d) inclusion of the parametrisation of the hard tissue geometry, features not adopted in any single study to authors' knowledge. Further, as military personnel use the head supported mass for operational activities and are subjected subfailure dynamic loads in all directions, and have women in the work force, the present study which applied subfailure spinal loading also has implications for this environment. Such safety devices may need improved assessment criteria in light of and along this line of research. Women assume more non-lordotic curvatures than men when seated in automotive seats [10]. The overriding influence of curvature on both anterior and posterior column responses which may affect the stability of disk and zygapophyseal joints, suggest its importance in the design of personalised safety systems.

V. ACKNOWLEDGMENTS

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