Contribution of Forces and Morphology to Segmental Rotation during Combined Loading of Cervical Spine: Investigation using Parametric Finite Element Models

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I. INTRODUCTION

The human cervical spine segments experience a combination of sagittal flexion-extension moments, axial compression-distraction forces, and anterior-posterior shear forces during inertial loads, encountered in motor vehicle and military environments [1]. Segmental rotation, which is the relative rotation of vertebrae with respect to each other, is used as a measure of the response of the spine. Experiments report considerable variations in segmental rotations for the same type of inertial loading. These experiments include post-mortem human subjects (PMHSs) [2], isolated head-neck PMHS complex [3] and volunteers [4-5]. Anatomical variations in head mass, neck musculature, and torso mass; and vehicle components such as seat back angle and headrest position contribute to differences in segmental rotation [2][6-8].

The differences in neck responses are also attributed to morphological variations in the cervical spine structure, including segment size, disc height, facet joints [9-12]. Some of these variations are a function of age and gender[6][9]. One of the gender dependent morphology is the anteroposterior spine dimension, i.e., vertebral depth. The vertebral depth is significantly lower ($p<0.05$) in stature-matched and head circumference-matched women compared to men[6][13]. The neck curvature in females is also different from males in the automotive seated posture [14-15].

While many experimental and modelling investigations have been conducted to determine the neck response in terms of intervertebral segmental rotation, a parametric investigation on the contribution of morphology and loading does not exist. The objective of this study was, therefore, to determine the influence of morphological and loading variations on segmental rotation under inertial loading conditions.

II. METHODS

Baseline and Morphed FE Models

This study utilised C5-C6 segment (Fig. 1) from a validated FE model of sub-axial cervical spine [16]. The FE mesh captured detailed geometry of the vertebrae. Soft tissues modelled in the intervertebral space included the asymmetric cervical disc (with posteriorly displaced nucleus), facet joints and ligaments (anterior longitudinal, posterior longitudinal, capsular, ligamentum flavum, interspinous). Material definitions used in previous human body models for cervical spine were used for the present study [18-19]. This segment served as the baseline model which was morphed using a mapping-block methodology [19-20]. This method used mapping blocks to encapsulate the mesh of the baseline model. The position of the nodes within each block transforms according to the movement of the blocks. Six morphological dimensions were parameterized: size of the segment, antero-posterior vertebral body depth, orientation of the vertebrae with respect to each other (segment orientation, measured in terms of Cobb angle, intervertebral disc height, facet joint articular processes height and facet joint articular processes slope (Table I).

A combined simultaneous loading of axial force, shear force, and flexion/extension moments was applied on the superior vertebra. The inferior vertebra, C6, was constrained in all degrees-of-freedom at its inferior nodes. The combined loading was applied in a period of 50 ms, simulating typical temporal loading histories. A FE preprocessor ANSA 17.1.0 (BETA CAE Systems) was used to generate the model and an explicit FE solver LS-DYNA R8.1.0 (LSTC) was used for the simulations.

Sensitivity Analysis

The parameters used in this study and their ranges are given in Table I. Twenty models were generated with

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simultaneous variation of the parameters. The parameter values were selected at three levels (maximum, mean, minimum) based on D-Optimal criteria [21]. The influence of these parameters was evaluated by a response-surface constructed using first-order polynomial. The axial force varied between 100N compression (positive) and 100N distraction (negative). The shear force varied between 100N anterior (positive) and 100N posterior (negative). The segmental rotation of each model was evaluated in terms of the change in Cobb angle. A total of forty models (twenty each for flexion and extension) were simulated for this study.

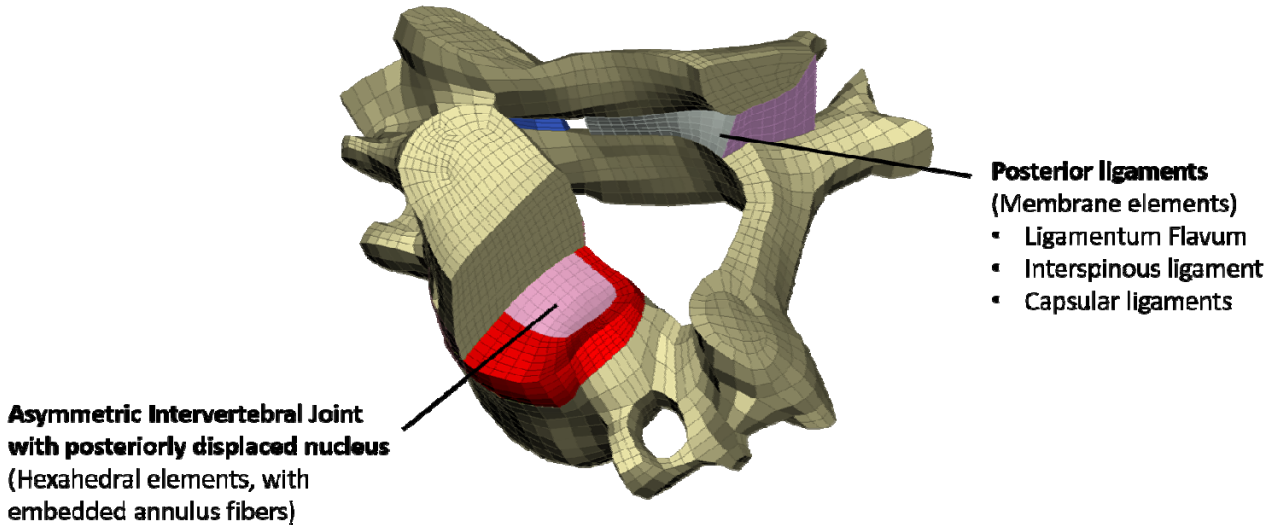

Fig. 1. Cross-section view of C5-C6 segment FE model used in this study. The major load bearing soft tissues and the type of elements used are labelled in figure.

TABLE I
PARAMETERS AND THEIR RANGES USED TO CONSTRUCT THE RESPONSE SURFACE

Type of variation	Parameter	Max Value	Min Value	References
Morphological Variation	Vertebral Depth	+10%	-10%	[6], [13]
	Segment Size	+10%	-10%	[6], [10]
	Segment Orientation (Cobb angle)	8°	2°	[14], [22]
	Disc Height	5.1 mm	4.6 mm	[10], [23]
	Facet Angle	45°	39°	[11], [12], [24], [25]
	Facet Height	6.5 mm	5.5 mm	[11], [12], [25]
Force	Axial Force	100 N	-100 N	[26]
	Shear Force	100 N	-100 N	[26], [27]

III. INITIAL FINDINGS

The contribution of forces and morphological variations to segmental rotation was evaluated based on the coefficients of the fitted response surface (Figure 2). The sensitivity analysis showed that, in flexion, shear force influenced the segmental rotation the most, followed by the segment size and axial force. In the extension, the most influential factor was shear force again, followed by axial force and vertebral depth. The coefficients of facet angle and facet height had negligible magnitudes in both flexion and extension.

IV. DISCUSSION

This study used a parametric FE model of the cervical spine to investigate the influence of variability in axial

(compression and distraction) and shear (anteroposterior and posteroanterior) forces and vertebral morphology on the segmental rotation. Linear polynomial response surfaces are frequently used in exploration of sensitivity of simulation variables [28]. Segmental rotation was analysed separately for flexion and extension. In flexion, the anterior spinal components are in compression while the posterior components are in tension. In extension, in addition to the anterior spinal components in tension and posterior components in compression, the response is non-linear due to the engagement of facet joints [29]. This difference in load-bearing mechanism necessitates a separate analysis for flexion and extension.

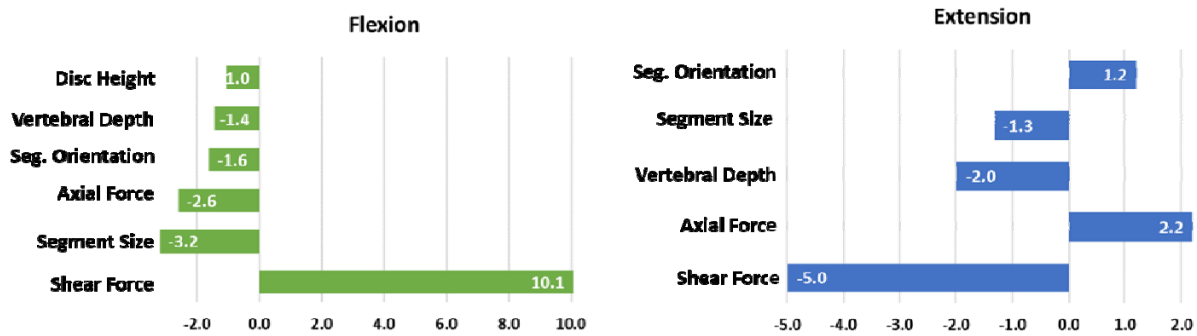

Fig. 2. Significance of forces and morphological parameters in flexion (Left) and extension (Right) combined loading. Numbers indicate coefficients of each parameter in the response surface. Positive shear force acts in anterior direction and positive axial force acts in caudal direction.

Influence of forces

The results of the sensitivity analysis indicated that the shear force was the most influential parameter in both flexion and extension, though the effect was opposite in the two loading cases. The axial force, however, had a smaller influence on segmental rotation compared to shear force. In flexion, the presence of anterior shear increased the segmental rotation; whereas in extension, it decreased the segmental rotation. Shear force on the neck due to inertial loading is dependent on factors like head mass, T1 acceleration, and orientation of neck during impact [1][3][29][30]. The influential role of shear force on response angle gives an insight into the large variation in segmental rotation observed in PMHS and volunteer studies. This is in line with the recent injury analysis wherein the lower neck injury criteria are expressed in terms of moments and shear forces [32].

Influence of morphology

Size of the segment had a considerable contribution to the segmental rotation; especially in flexion loading, where it has more influence than the axial force on the segment. It should be noted that in both flexion and extension, the size of the segment has a negative influence on the segmental rotation. In other words, a larger segment would sustain lower segment rotation. This could be a reason why women, who have smaller vertebra even when stature matched, exhibit more segmental rotation under same loading conditions [6][32].

Vertebral depth also had a negative influence in both moment loading modes, with higher influence in extension. Although earlier whiplash-based study noted that vertebral depth is an influential gender-dependent factor [20], the current study showed that even with variations in axial and shear forces, vertebral depth plays a role on segmental response. Followed by the vertebral depth, vertebral orientation showed moderate influence with opposite effects in flexion and extension. Disc height had the least influence on the segmental rotation in flexion loading, whereas, the influence was negligible in extension.

Since the vertebral morphology, along with the direction and magnitude of forces, influenced segmental rotations, this study suggests that pre-test dimensions of test specimens should be measured in physical and virtual experiments. Vertebral dimensions should be treated as a potential variable that influences experimental outputs, especially intervertebral kinematics. A limitation of this study was that all loads were applied simultaneously, and therefore, the influence of phase differences in the different loads were not investigated in this study. In conclusion, although previous studies had investigated the influence of different loading conditions, this is the first study to include the variability in vertebral morphology in a sensitivity analysis. The relative significance of morphological variations with respect to axial and shear forces shows the need for

further detailed studies with expanded experimental design to capture the interaction of loads and morphological variations.

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