Sensitivity Study of Upper Spine Ligaments for a Head and Neck Finite Element Model

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Abstract This finite element study aims to understand the role of upper spine ligaments during physiological motion in a C0-T1 finite element model (FEM). One of the most critical joints in the cervical spine is the occipital-atlantoaxial joint, which is responsible for various motions of the head. The current C0-C2 FEM includes various ligaments, such as alar, transverse, nuchal, capsular, apical, tectoria and cruciform. Notably, the C0-C2 joint lacks an intervertebral disc, which contributes to its greater range of motion compared to the lower cervical spine (C3-C7).

Finite element analysis with detailed upper spinal ligament modeling indicates that during flexion, the posterior atlantoaxial membrane and the posterior atlanto-occipital membrane exhibit the highest levels of strain, underscoring their importance in limiting forward movement and protecting the spinal structures from hyperflexion. And during extension, the anterior atlantoaxial membrane and the anterior atlanto-occipital membrane experience the maximum strain, highlighting their pivotal role in resisting excessive backward motion and maintaining anterior stability. These results provide valuable insights into the biomechanical contributions of the upper cervical ligaments in maintaining stability during instances like whiplash.

Keywords Functional Spinal Unit (FSU), atlantoaxial joint, ligamental strain, ligament activation, finite element analysis (FEA).

I. INTRODUCTION

The craniovertebral junction (C0-C2) is highly susceptible to injuries such as whiplash and presents unique challenges in surgical procedures like spinal fusions, screw fixations, and craniovertebral arthrodesis. Understanding its biomechanics is critical for improving clinical outcomes. Biomechanical models, including in vitro and finite element (FE) models, provide essential insights into injury mechanisms and dysfunction, advancing prevention, diagnosis, and treatment strategies [1]. The FE method offers a powerful tool for analysing both qualitative and quantitative aspects, enabling detailed investigation of local structures and addressing limitations of in vitro and in vivo approaches [2]. Advanced 3D FE models derived from CT scan data offer valuable insights into the biomechanical roles of ligaments and cartilage in the upper cervical spine [3]. However, current head and neck FE models face limitations in accurately replicating the full range of motion (ROM) of this region. Recent research underscores the necessity of incorporating tissue strain due to repositioning in FE models to enhance the understanding and prediction of injury mechanisms [4]. A prerequisite to ligament strain analysis is a thorough investigation of ROM. Zhang *et al*. utilised numerical techniques to study the ROM of the C0-C2 complex under physiological static loading across all degrees-of-freedom. Their findings highlighted that ligament laxity contributes significantly to the large ROM observed in this region, emphasising the critical need for precise ligament modeling in advanced biomechanical analyses [5]. Nightingale *et al.* analysed the cervical spine and confirmed that the upper cervical region exhibits significantly greater range of motion (ROM) compared to the lower cervical spine [6]. To validate these findings in vitro, Dibb *et al.* investigated normalised axial forces and sagittal plane moments in the upper cervical spine using post-mortem human subject (PMHS) ligamentous specimens, providing critical biomechanical insights [7]. The present study focuses on understanding the importance of the upper spine ligaments in the head and neck

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complex. As part of building a detailed FEM, the ligaments, including the alar ligament, the transverse ligament, the cruciform, upper and lower crux, have been modeled in the upper cervical spine in the head and neck FEM. The study finds the ligament sensitivity for the sagittal physiological motion.

II. METHODS

An existing validated Head and Neck Model developed by Medical College of Wisconsin, along with the morphometry referred from literature, were used in this study [8]. The material properties of the skull were assumed to be rigid and the spine components, like cortical and trabecular, were assumed to be linear elastic. The detailed values for various materials are given in Table I. The ligaments were modeled using shell elements and a fabric material model was incorporated. A constrained nodal rigid body set was formed from the superior articular facets of C0 to T1 and an incremental moment load of 1.5 Nm was applied. The inferior surface of the T1 vertebral was fully constrained. The flexion and extension moment of the head and neck was carried out on the FEM. Following the validation of the ROM using previous literature, the ligament strain at 1.5 Nm moment load was analysed, and the ligament exhibiting the maximum sensitivity through deformation was identified.

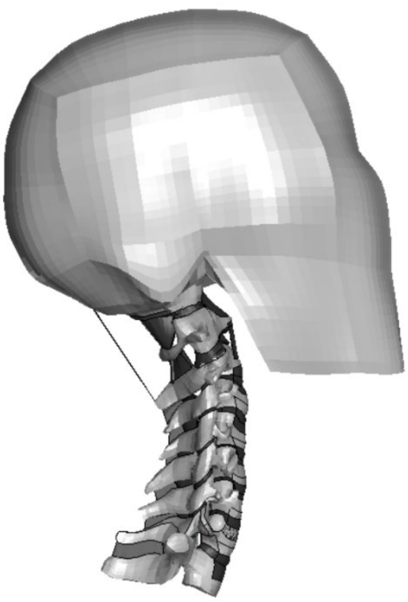

Fig. 1. Side view of the developed Head and NeckModel.

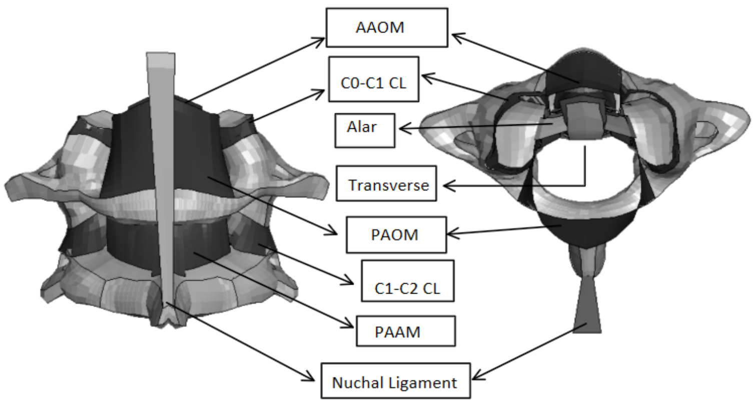

Fig. 2. Front and top view of the C0-C2 with ligaments.

The inital focus of the work was on a detailed morphometric analysis of the C0-C2 functional unit based on the experimental data and FEMs. In addition, the ligaments such as the alar ligament, the transverse ligament, the cruciform, upper and lower crux were modeled. The head and neck (C0-C7) FEM was run using LS-DYNA to find the ligament strain and stress on cartilages during the saggital ROM to understand its sensitivity.

TABLE I
MATERIAL PROPERTIES OF VARIOUS COMPONENTS USED IN THE DEVELOPED FINITE ELEMENT MODEL

Material	Element Type	Young's Modulus (GPa)	Poisson's Ratio		Material	Element Type	Young's Modulus (GPa)	Poisson's Ratio
Cortical Bone	Shell	18.54000	0.3		Transverse	Shell	1.00E-06	0.3
Trabecular	Solid	0.442	0.3		Nuchal	Shell	0.01	0.49
Cartilage	Solid	0.01	0.4		ISL	Shell	1.00E-06	0.3
End Plates	Shell	5.599999	0.3		Apical	Shell	1.00E-06	0.3
ALL	Shell	1.00E-06	0.3		Tectoria	Shell	1.00E-06	0.3
PLL	Shell	1.00E-06	0.3		Cruciform	Shell	1.00E-06	0.3
CL (C0-C2)	Shell	0.01	0.3		Facet Fluid	Solid	0.56	0.3

CL (C3-C7)	Shell	1.00E-06	0.3		Annulus	Shell	0.006985	0.3
CL (C7-T1)	Shell	1.00E-06	0.3		Ligament Flavum	Shell	1.00E-06	0.3
Alar	Shell	0.005	0.3					

TABLE II
COMPARISON OF ROM OF PRESENT STUDY WITH PUNJABI *ET AL.* 1988 & 2001 AND GOEL *ET AL.* 1988 [9-11]

	Panjabi *et al.* (1988) [10]		**Goel *et al.* (1988) [9]**		**Panjabi *et al.* (2001) [11]**		**Present Study**	
Level	C0-C1	C1-C2	C0-C1	C1-C2	C0-C1	C1-C2	C0-C1	C1-C2
Moment (Nm)	1.5		0.3		1		0.3	
Flexion (deg.)	3.5 (0.6)	11.5 (2.0)	6.5 (2.5)	4.9 (2.0)	7.2 (2.5)	12.3 (2.0)	4.1	6.3
Extension (deg.)	21.0 (1.9)	10.9 (1.1)	16.5 (7.6)	5.2 (2.9)	20.2 (4.6)	12.1 (6.5)	9.8	12.1
Axial Rotation (deg.)	7.9 (0.6)	38.3 (1.7)	2.4 (1.2)	23.3 (11.2)	4.9 (3.0)	28.4 (4.8)	7.6	10.3
Lateral Bending (deg.)	5.6 (0.7	4.0 (0.8)	3.4 (2.8)	4.2 (2.8)	4.5 (1.5)	3.3 (2.3)	6.4	5.3

III. RESULTS

The FEM was compared with [9-11] under the quasi-static 0.3 Nm moment applied along the Y-axis at C0, as per [10] the flexion angles were 4.13° and 6.34° while the extension angles were measured as 9.78° at C0-C1 and 12.1° at C1-C2. These values (Table II) were found to be consistent with those reported in the literature [9-11]. The results also validate that extension has a higher ROM than flexion [12]. The ligament strains were also analysed. It can be inferred that in the sagittal plane motion, that is flexion and extension, the atlanto-occipital, atlantoaxial membrane and nuchal faced maximum displacement. This means that these ligaments play a major role in restricting the sagittal plane motion.

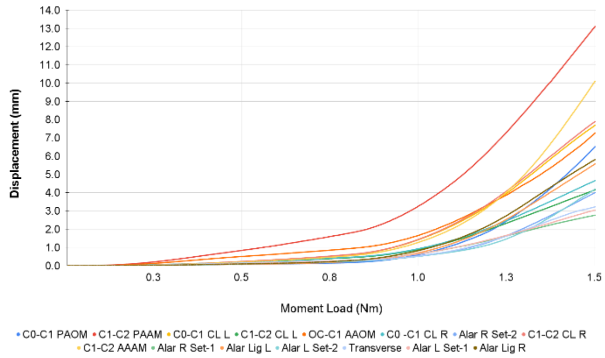

Fig. 3. Displacement vs Load Diagram for Flexion.

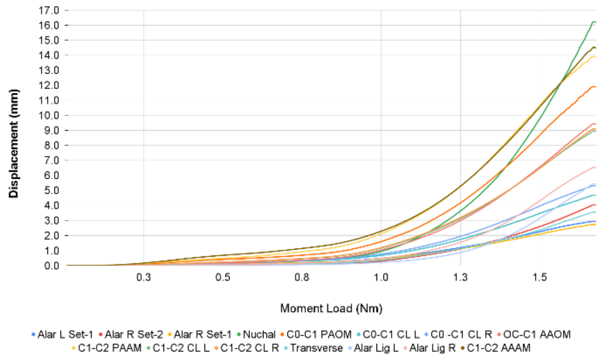

Fig. 4. Displacement vs Load Diagram for Extension.

During flexion, the average ligamental strain at the posterior atlanto-occipital membrane was 0.537, followed by posterior atlantoaxial membrane of 0.23. During extension, the ligamental strain at the anterior atlanto-occipital membrane was 0.13, followed by anterior atlantoaxial membrane of 0.102. Since the nuchal ligament tends to compress more, we see more strain development in extension as compared to flexion. During flexion, 0.334 of strain was seen on nuchal ligament, whereas during extension it was 0.893.

Alar L Set-1	0	0	0.1	0.2	0.3	0.4	0.8	1.3	2.1	3	2.82
Alar L Set-2	0	0	0.1	0.1	0.2	0.3	0.7	1	2.3	2.6	3.68
Alar L Set-3	0	0	0.1	0.1	0.2	0.3	0.7	1.8	3.5	2.8	5.06
Alar R Set-1	0	0	0.1	0.2	0.3	0.4	0.7	1.3	2	2.7	2.6
Alar R Set-2	0	0	0.1	0.1	0.2	0.3	0.8	1.2	2.4	3.3	3.58
Alar R Set-3	0	0	0.1	0.1	0.2	0.4	0.9	2	3.8	3.8	5.32
Nuchal	0	0	0	0.1	0.2	0.3	1.1	1.8	4.1	3.9	6.84
C0-C1 PAOM	0	0	0.1	0.1	0.2	0.3	1.1	1.7	3.7	3.9	5.72
C0-C1 CL L	0	0	0.2	0.3	0.5	0.8	1	3	5.2	3.5	7.11
C0 -C1 CL R	0	0.1	0.2	0.3	0.4	0.6	0.8	1.9	3.2	3.3	4.29
C0-C1 AAOM	0	0.1	0.4	0.6	0.9	1.1	0.9	3.1	4.9	3.4	6.59
C1-C2 PAAM	0	0.2	0.6	1.1	1.6	2.2	1.1	5.8	9.2	3.9	12.1
C1-C2 CL L	0	0.1	0.1	0.3	0.4	0.5	0.9	1.8	2.9	3.4	3.85
C1-C2 CL R	0	0.1	0.2	0.3	0.5	0.8	0.9	3.1	5.4	3.4	7.29
Transverse	0	0	0.1	0.2	0.3	0.3	0.7	1.2	2.2	2.7	3.02
C1-C2 AAAM	0	0	0.1	0.3	0.5	0.7	0.8	2.9	5.8	3.1	8.94

Fig. 5. Heat Map for the displacement values for flexion at 1.5 Nm Load.

Alar L Set-1	0	0	0	0.2	0.1	0.2	0.4	0.7	1.2	1.9	2.65
Alar L Set-2	0	0	0	0.2	0	0.1	0.2	0.5	1.1	2.1	3.52
Alar L Set-3	0	0	0	0.2	0.1	0.1	0.2	0.4	0.9	2.2	4.36
Alar R Set-1	0	0	0	0.2	0.1	0.2	0.3	0.7	1.1	1.8	2.46
Alar R Set-2	0	0	0	0.2	0	0.1	0.2	0.5	1.1	2.1	3.33
Alar R Set-3	0	0	0	0.3	0.1	0.2	0.3	0.8	1.6	3.2	5.54
Nuchal	0	0	0	0.2	0.2	0.3	0.6	1.6	3.8	7.4	13
C0-C1 PAOM	0	0	0.1	0.2	0.5	0.7	1.2	2.3	4.3	7.1	10.4
C0-C1 CL L	0	0	0.1	0.2	0.2	0.3	0.5	1	1.8	2.9	4.12
C0 -C1 CL R	0	0	0.1	0.2	0.2	0.4	0.6	1.1	2	3.3	4.7
C0-C1 AAOM	0	0	0	0.2	0.2	0.4	0.7	1.6	3.1	5.3	8.09
C1-C2 PAAM	0	0	0.2	0.2	0.6	0.9	1.6	3	5.4	8.8	12.5
C1-C2 CL L	0	0	0.1	0.2	0.3	0.5	0.9	1.7	3.2	5.3	7.81
C1-C2 CL R	0	0	0.1	0.2	0.3	0.5	0.9	1.8	3.3	5.3	7.88
Transverse	0	0	0	0.2	0.1	0.1	0.3	0.6	1.2	1.9	3
C1-C2 AAAM	0	0	0.2	0.5	0.8	1.2	1.8	3.1	5.4	8.7	12.7

Fig. 6. Heat Map for the displacement values for extension at 1.5 Nm Load.

A displacement versus force analysis revealed the activation force and activation time at which the ligament transitions to its non-linear behaviour (Fig. 3 and Fig. 4). The study indicated that ligaments subjected to greater loads exhibited larger deflections and displacements. During extension, the anterior membranes bore the majority of the load, while flexion primarily engaged the posterior membranes, aligning with previous findings (Fig. 5 and Fig. 6).

IV. DISCUSSION

This study developed a detailed C0–T1 FEM of the head and cervical spine, derived from the precise geometries of PMHS specimens, to analyse segmental ROMs under rotational moment loading. The ROM of the upper cervical spine was also validated individually. The greater ROMs observed in the C0–C2 motion segments can be attributed to their unique anatomical features. Unlike other spinal levels, the C0–C2 complex lacks intervertebral discs, with the vertebrae connected solely by ligaments and joint articulations. The inherent laxity of the upper cervical ligaments enables small loads to generate significant rotational motion within the complex [9]. This study validates the accuracy of the developed FEM in replicating cervical spine biomechanics. Under a 0.3 Nm load case [9-11], the alar ligament was found to play a critical role in restricting lateral bending and axial rotation, while also contributing significantly to limiting flexion and extension, highlighting its importance in cervical stability. The effective plastic strain in the alar ligament gradually increased up to a 0.3 Nm load, with flexion causing greater strain compared to extension. The range of motion of the present study is compared with the studies of Panjabi *et al.* [10-11] and Goel *et al.* [9].The ligament sensitivity analysis using the heat maps in Fig. 5 and Fig. 6 shows that during flexion, the posterior atlantoaxial membrane and the posterior atlanto-occipital membrane exhibit the highest levels of strain, underscoring their importance in limiting forward movement and protecting the spinal structures from hyperflexion. And during extension, the anterior atlantoaxial membrane and anterior atlanto-occipital membrane experience the maximum strain, highlighting their pivotal role in resisting excessive backward motion and maintaining anterior stability.

V. CONCLUSION

The developed FEM effectively replicates the biomechanical behaviour of the human cervical spine, validated through ROM analysis and a detailed sensitivity assessment of ligament tension. The upper cervical spine, characterised by its extensive ROM, is crucial for cervical biomechanics. This study underscores the critical role of ligaments and cartilage in maintaining cervical spine stability across diverse motions, offering significant insights into injury mechanisms and advancing the understanding of clinical management strategies.

VI. ACKNOWLEDGEMENTS

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