A Detailed Finite Element Modelling and Validation of the Occipital-Atlanto-Axial joint complex

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Abstract

The C0–C2 complex is crucial for cervical spine motion and frequently involved in clinical procedures. This study presents a validated finite element model of the C0–C2 region, integrating cartilage and major ligaments using GHBMC data and literature-based parameters. The model showed strong agreement with experimental ROM and ligament strain data. Simulations confirmed the stabilizing roles of ligaments, particularly the nuchal and the capsular ligaments. This model provides a platform for studying upper cervical biomechanics in both clinical and injury scenarios.

Methodology

Literature Review & GHBMC Data Extraction
Identifying morphometric parameters

Geometry Modelling
Developed Atlas (C1) and Axis (C2) using extracted data

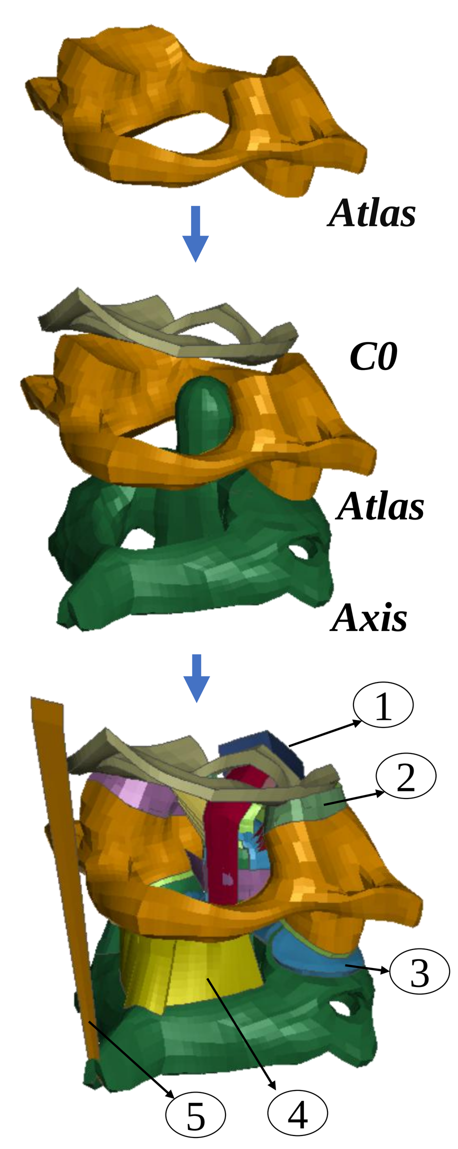
C0 – C2 Integration
Assemble the complete model with ligaments and cartilages

Meshing (ANSA Beta)
Generate high – quality finite element mesh

Material Assignment and Loading
Assign material properties and apply boundary conditions

Simulation and validation (LS – Dyna)
Perform simulations; compare ROM with Literatures

Ligament Strain
Analyse strain at different loads



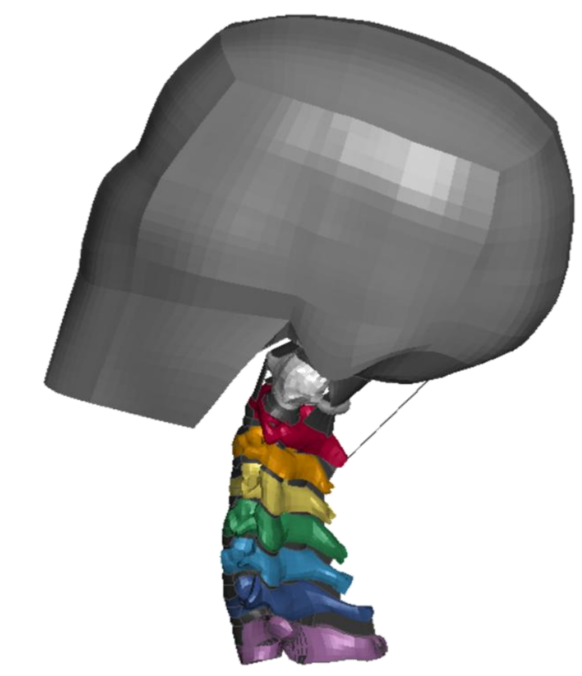
Developed Model

1- Anterior Atlanto-Occipital Membrane; 2- Capsular Ligaments; 3- Cartilage; 4- Posterior Atlanto Axial Membrane;5- Nuchal

Introduction

The upper cervical spine (C0–C2), comprising the occiput, atlas (C1), and axis (C2), is highly mobile and anatomically distinct. Unlike the lower cervical spine, it lacks intervertebral discs and depends entirely on bony articulation and ligamentous support for stability and motion. Understanding ligament biomechanics is essential in injury and surgical contexts.

The purpose of this study was to create a high-fidelity, anatomically accurate FE model of the C0–C2 complex incorporating precise bone shape, cartilage interfaces, and all key ligaments to analyze their separate biomechanical functions during physiologic loading.



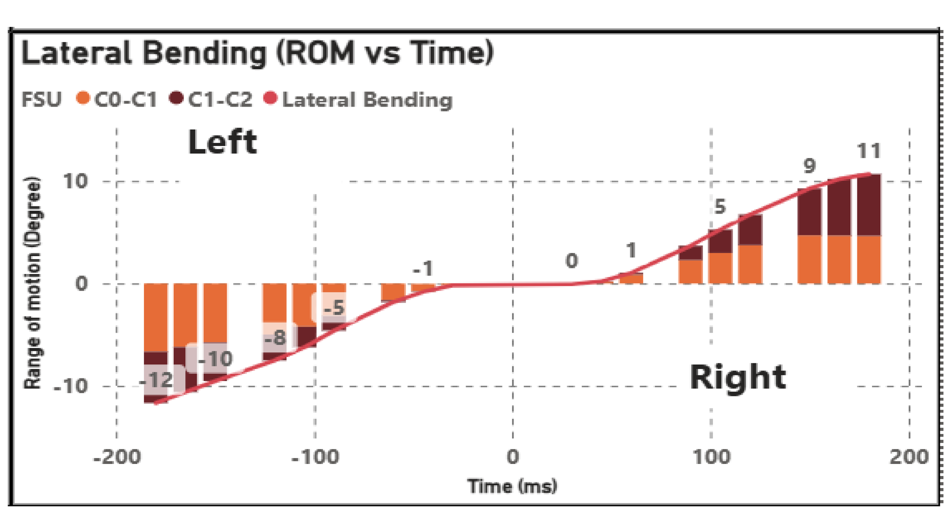
Materials

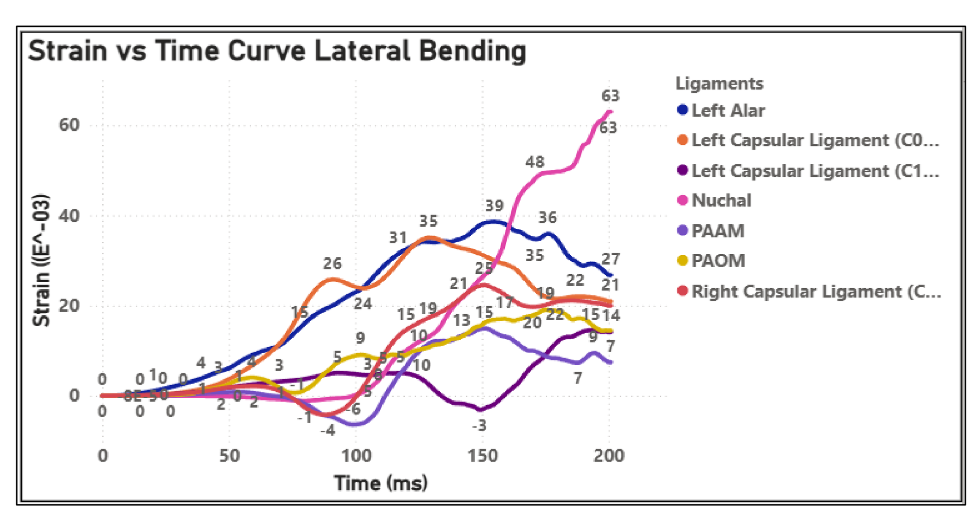
Bones and cartilage were modelled using solid elements, while upper cervical ligaments were represented with shell elements to reflect their biomechanical function. Material properties like Young's modulus and density were assigned from literature to ensure physiological accuracy. Below are some ligaments and their assigned properties.

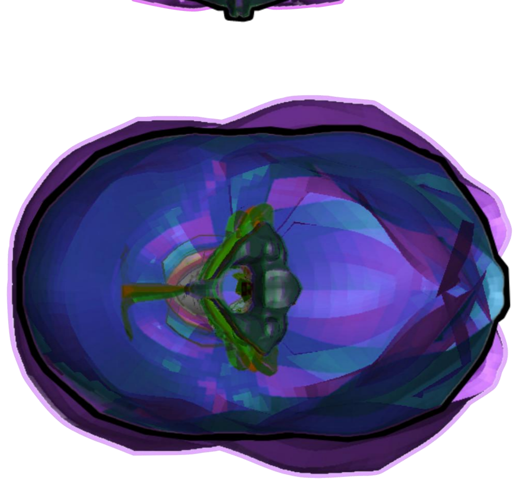
Parts	Alar	Transverse	Capsular	Trabecular
Geometry				
Element Type	Shell	Shell	Shell	Solid
Material Model	Fabric (Orthotropic)	Fabric (Orthotropic)	Fabric (Orthotropic)	Piecewise Linear Plasticity
Density (kg/mm ^{3})	1×10^{-6}	1×10^{-6}	1×10^{-6}	1×10^{-6}
Thickness (mm)	2.9	1.1	2	-
Youngs Modulus (MPa)	5	1×10^{-3}	10	442

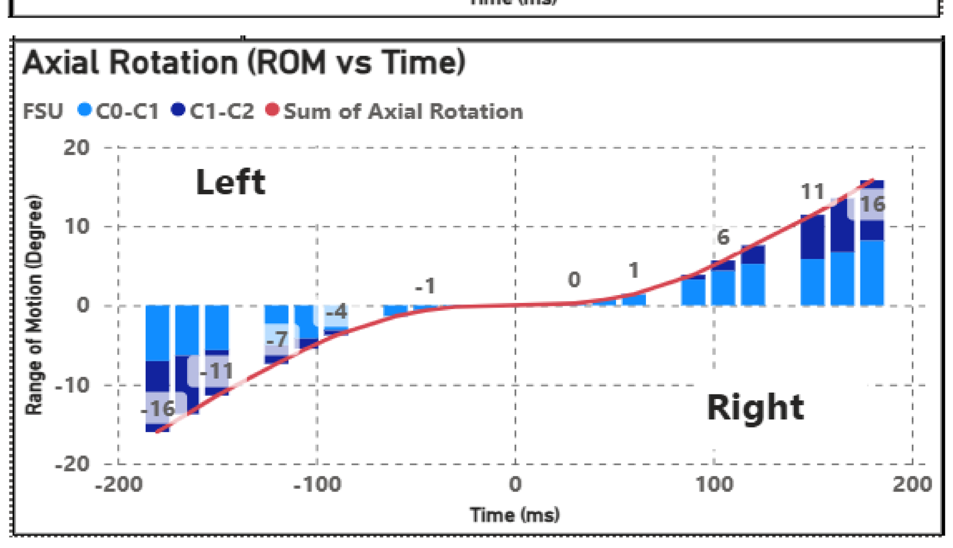
Simulation Results

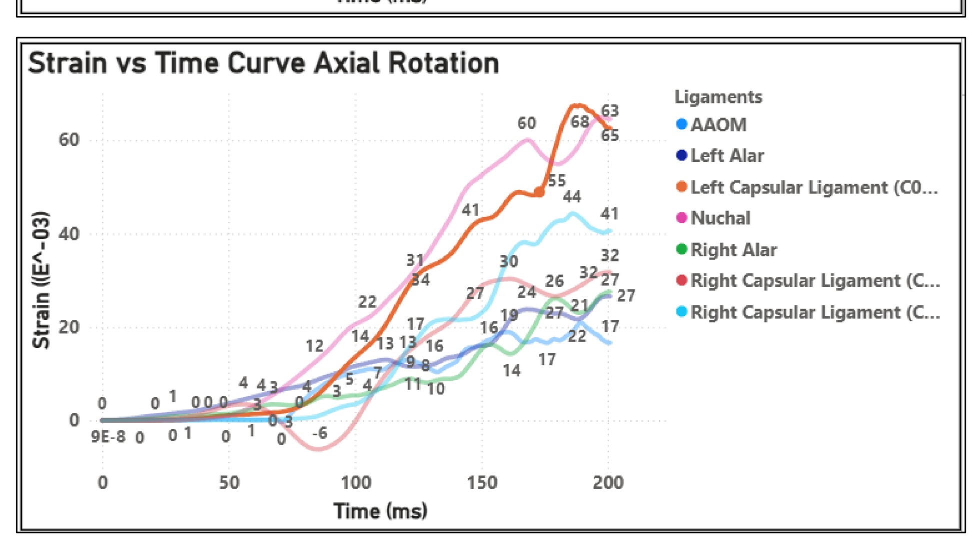
The validated finite element model of the C0–C2 complex demonstrated physiologically consistent behavior under various loading conditions. The following key outcomes were observed:

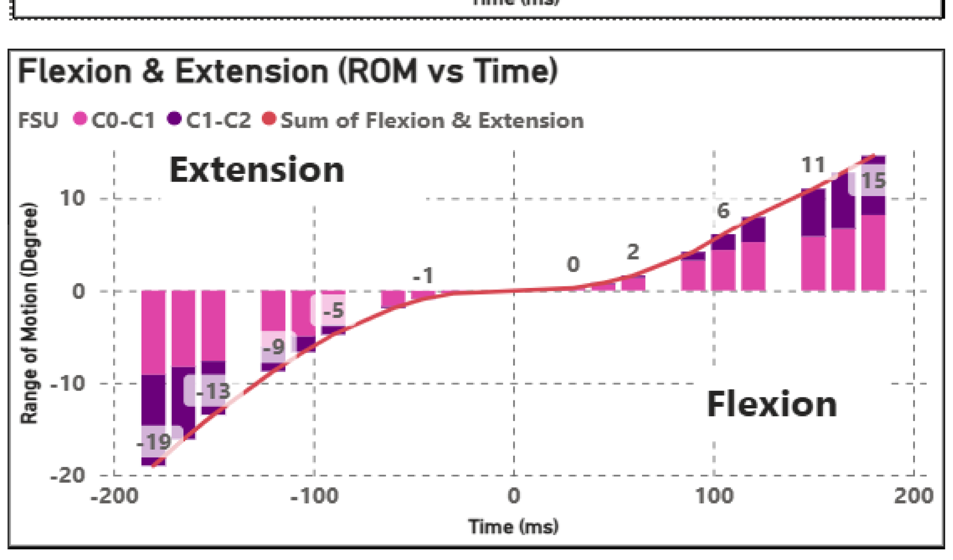


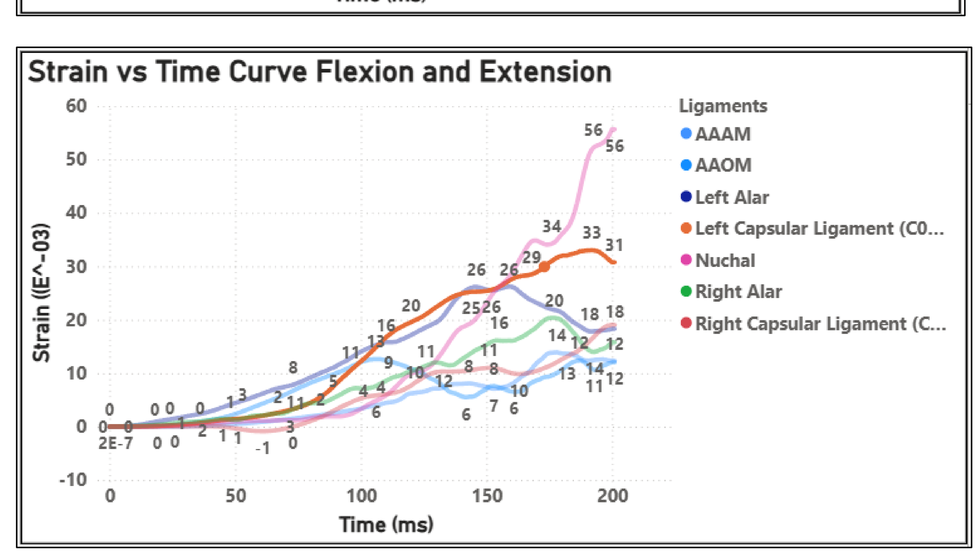












C0-C1	Punjabi (1988)	Goel (1988)	Punjabi (2001)	*Left/ Anterior	*Right/ Posterior
Load	1.5	0.3	1	0.3	0.3
Lateral Bending	5.6 (0.7)	3.4 (2.8)	4.5 (1.5)	6.42	6.27
Axial Rotation	7.9 (0.6)	2.4 (1.2)	4.9 (3)	7.6	9.12
Flexion	3.5 (0.6)	6.5 (2.5)	7.2 (2.5)	4.13	-
Extension	21 (1.9)	16.5 (7.6)	20.2 (4.6)	-	9.78

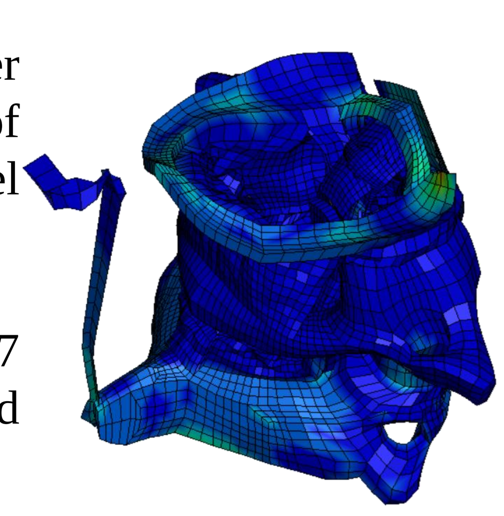
***Current model**

C1-C2	Punjabi (1988)	Goel (1988)	Punjabi (2001)	*Left/ Anterior	*Right/ Posterior
Load	1.5	0.3	1	0.3	0.3
Lateral Bending	4 (0.8)	4.2 (2.8)	3.3 (2.3)	5.26	3.72
Axial Rotation	38.3 (1.7)	23.3 (11.2)	28.4 (4.8)	10.3	8.43
Flexion	11.5 (2.0)	4.9 (2.0)	12.3 (2.0)	6.34	-
Extension	10.9 (1.1)	5.2 (2.9)	12.1 (6.5)	-	12.1

***Current model**

Conclusion

- The developed FE model replicates C0–C2 biomechanics under physiological bending. Results highlight the key stabilizing roles of ligaments and articular cartilage. Shown beside is the C0–C2 model illustrating ligament strain distribution at C0 during extension.
- Integration with a validated C2–C7 model will yield a full C0–C7 spine, enabling dynamic simulations, injury analysis, and personalized surgical planning.



Discussion and Future Scope

The integrated C0–C7 model will support:

- Crash and whiplash injury simulations
- Evaluation of surgical techniques (e.g., odontoid screw fixation)
- Development of patient specific implants and treatment planning.