Development and Validation of Human Head-Neck FE Model for Simulating Soft Tissue Injury in Cervical Spine

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INTRODUCTION

Cervical spinal injuries are most frequently the result of road traffic crashes. The commonly injured neck structures associated with whiplash include facet capsule, the intervertebral discs and the cervical ligaments. Different mechanisms have been hypothesized to explain neck injuries in whiplash [1]. The shear force causing stretch of the facet capsules have been implicated as the most common source of complaints associated with soft tissue neck injury [2]. This mechanism was further explored on human cadavers in simulated rear-end collisions [3].

This study reports the development and validation of an Finite Element (FE) model of an adult male cervical spine integrated with a detailed human head model. The head-neck complex was exercised to predict the cervical soft tissue response in simulated cadaver rear-end impact experiments.

FE NECK MODEL DEVELOPMENT

Cervical Spine Geometry

The geometry of the cervical spine was obtained from CT scans of a 64 years old male subject. The surfaces of the seven cervical vertebrae, the first thoracic vertebra and intervertebral discs were rendered using MIMICS (Materialise, Belgium) (Fig. 1). 3-Matics (Materialise, Belgium) was applied to refine and restore the facet surface profiles (Fig. 2). The surface data was then imported to Hypermesh 12.0 (Altair, MI) to create the FE surface mesh. The surface mesh was then further smoothened using Meshworks 5.0 (DEP, MI).

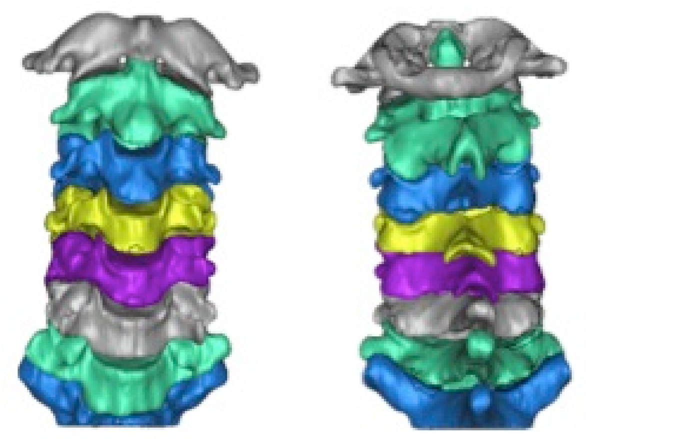

Fig. 1: CAD rendering of the neck surface geometry

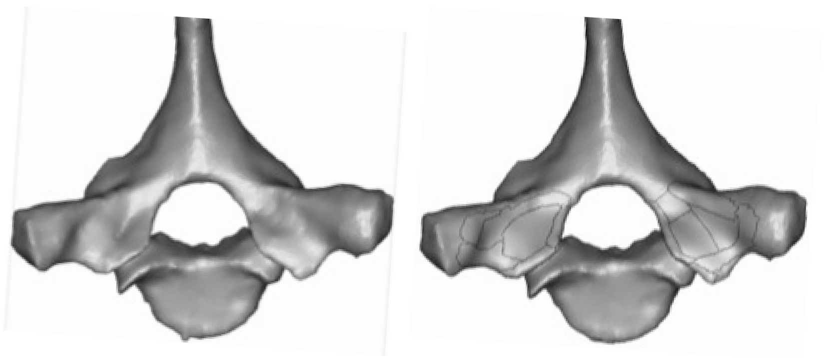

Fig. 2: C7 facet surface profiles before (left) and after (right) reconstruction

FE Mesh Technique

ANSYS ICEM CFD 12.1 (ANSYS INC, PA) was used to develop hexahedral element mesh for each vertebra. This base-block mesh can be projected to the new geometry of the same vertebral segment or any vertebra with similar geometry to save the mesh development cost. Fig. 3 shows the block mesh constructed for C4 vertebra.

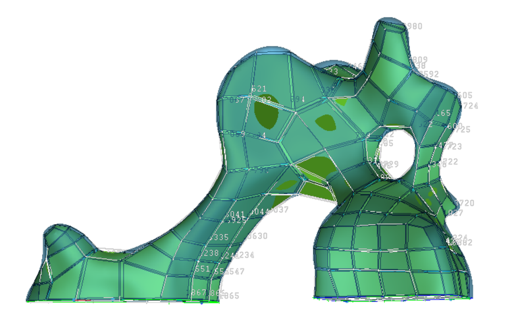

Fig. 3: An example block mesh for C4

FE Neck Model

Intervertebral Disc

The intervertebral discs (Fig. 4) consisted of the nucleus, annulus, fibers and endplates. The disc components were meshed with hexahedral elements except fibers which were meshed with shell.

Facet Joint

The facet joint (Fig. 5) consisted of capsular ligaments (beam elements) and cartilage (shell elements).

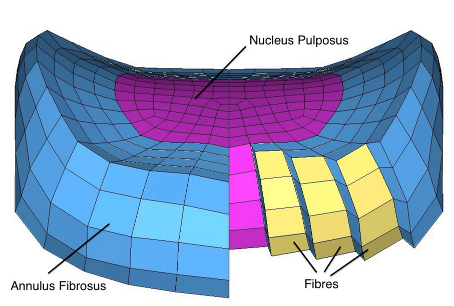

Fig. 4: Intervertebral disc

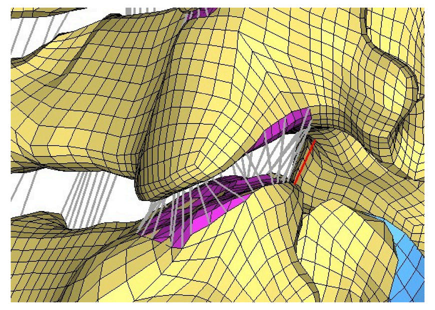

Fig. 5: Facet joint capsule exposed

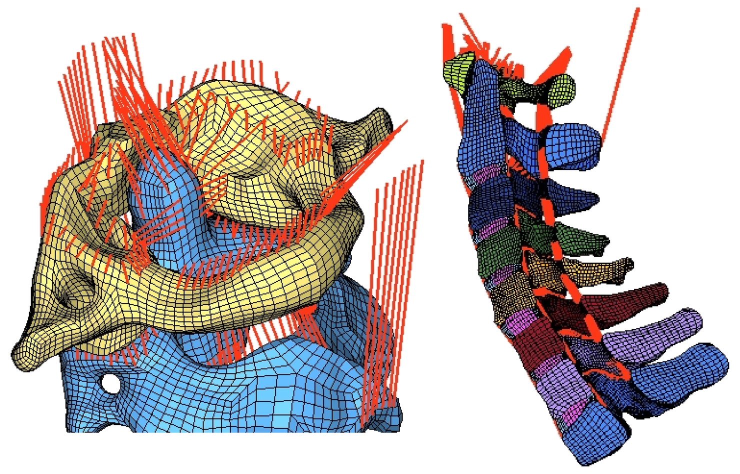

Fig. 6: Cranio-vertebral ligaments and other major cervical spinal ligaments with vertebral bodies

Cervical spine ligaments

Beam/bar elements
- Anterior longitudinal ligaments (ALL)
- Posterior longitudinal ligaments (PLL)
- Capsular ligaments (CL)
- Ligamentum flavum (LF)
- Interspinous ligaments (ISL)
- Alar ligament
- Cruciate ligament

Cranio-vertebral ligaments/membranes

Beam/bar elements
- Atlanto-axial ligament
- Apical ligament of dens
- Anterior atlanto-occipital ligament
- Anterior atlanto-occipital membrane
- Posterior atlanto-occipital membrane

Some of the major muscles

Beam/bar elements
- Illiocostalis
- Longus muscles group
- Multifidus
- Oblique capitis
- Rectus capitis
- Scalene
- Semisplenius
- Sternocleidomastoid
- Trapezius

Integration of Head and Neck Model

The neck model was integrated with the Wayne State University Human Head Injury Model [4] developed and validated previously

Components	No. of Elements
Vertebral body	123,348
Intervertebral disc	17,010
Ligament	873
Muscles	182
Facet joint	2,366
Neck	144,179
Head	330,000

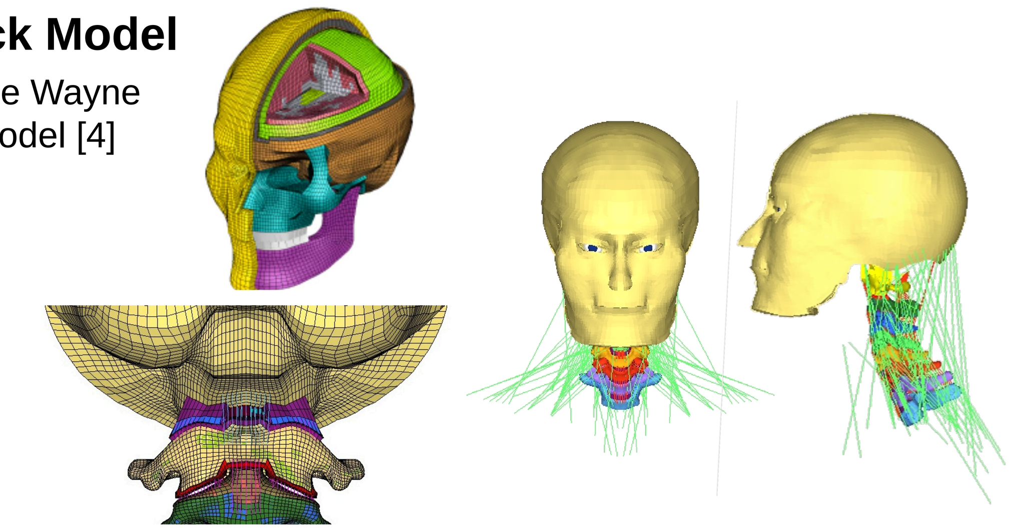

Fig. 7: WSU head model by Zhang et al. (2001), an integrated cervical spine and head model, and detailed view of the atlanta-occipital joint

FE HEAD/NECK MODEL VALIDATION

Head-Neck Drop Tests

Nine cadaveric head-neck drop tests [5] (Fig. 8):
- Rigid anvil in -15, 0, 15 degree angles in the sagittal plane
- Impact velocity of 3.2 m/s
- Measured head resultant force
- Measured T1 neck axial and shear force

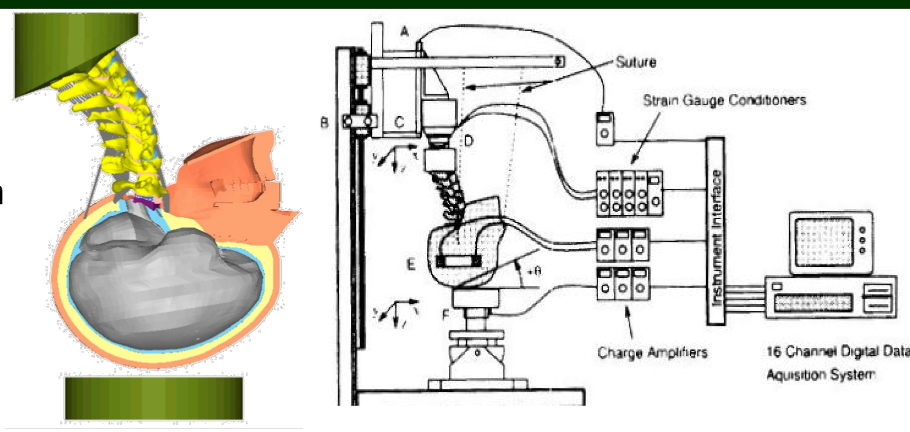

Fig. 8: Drop test setup (Nightingale et al.,1997)

Validation Results

Fig. 9 shows the FE model predicted force time responses at anvil angles of -15, 0 and +15 degrees. The model results agreed well with the test results.
Failure strain 0.01 and 0.03 was set for spongy and cortical vertebrae to simulate cervical vertebral fracture. The model predicted bone vertebrae fracture for two cases matched with experimental findings.

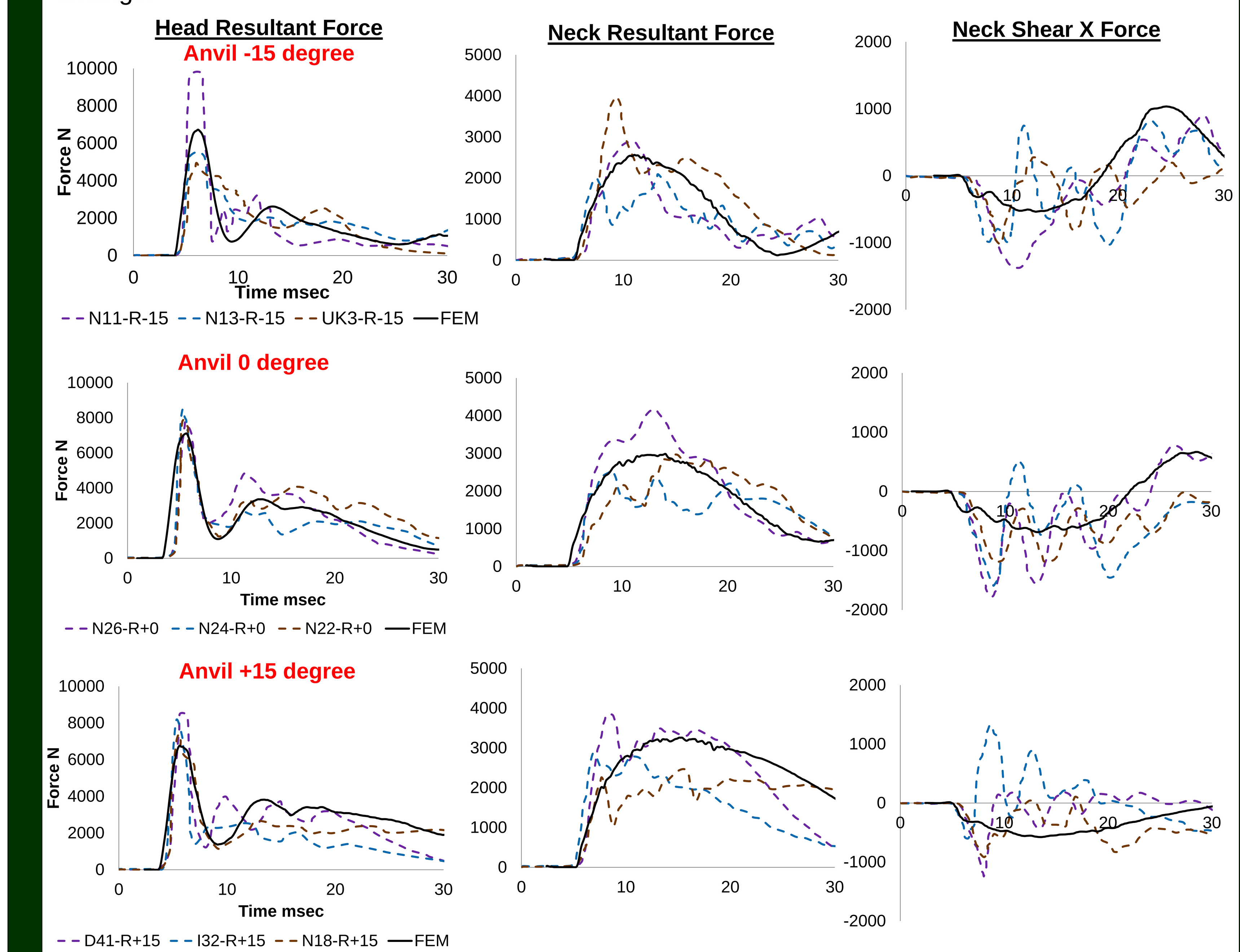

Fig. 9: Head-neck model prediction in comparison with cadaver head-neck drop test results at three impact angles

Validation Assessment: CORA

CORA 3.6 2012 (released by PCB, Germany)[6] was used to subjectively determine the model correlation with the experimental data. The overall rating based on corridor and correlation methods were in the range of 0.48-0.87(1 is perfect match).

Force Parameters	Overall CORA Rating		
	0 Degree	+ 15 degree	- 15 degree
Head Res	0.867	0.483	0.8015
Neck res	0.745	0.484	0.62
Neck Shear	0.641	0.500	0.647

REAR-END IMAPCT SIMULATION

Rear-End Impact Experiments

The head-neck model complex was applied to simulate PMHS rear-end impact tests (Fig. 10) reported by [3].
- Rear-end impacts at sled velocities of 8 and 16 kph, with and without headrest
- T1 acceleration traces were applied to the FE model
- Vertebral body's displacement in the sagittal plane was analyzed from the targets implanted in the cadaver cervical vertebral body captured by a bi-planar x-ray system

Fig. 10: Cadaver tests by White et al. (2009)

Model Simulation Results

Head Displacement

- FE model predicted vertebral body angular displacements were comparable to the test results. (Fig. 11-b)

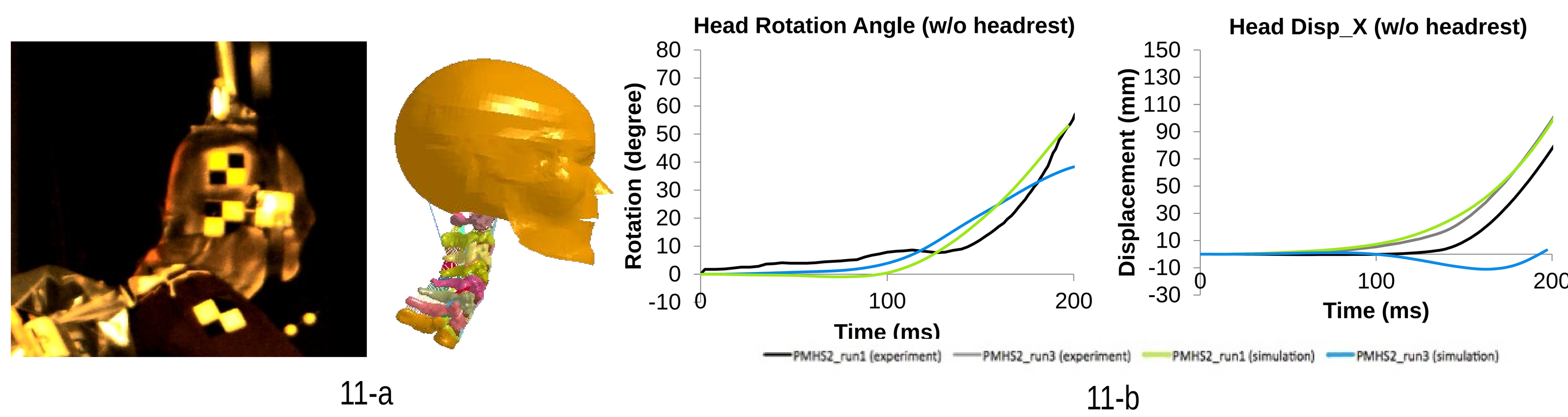

Fig. 11: a) Model set up comparison; b)Model predicted head rotation, head displacement x vs. experimental data without headrest

Neck Vertebral Body Kinematics

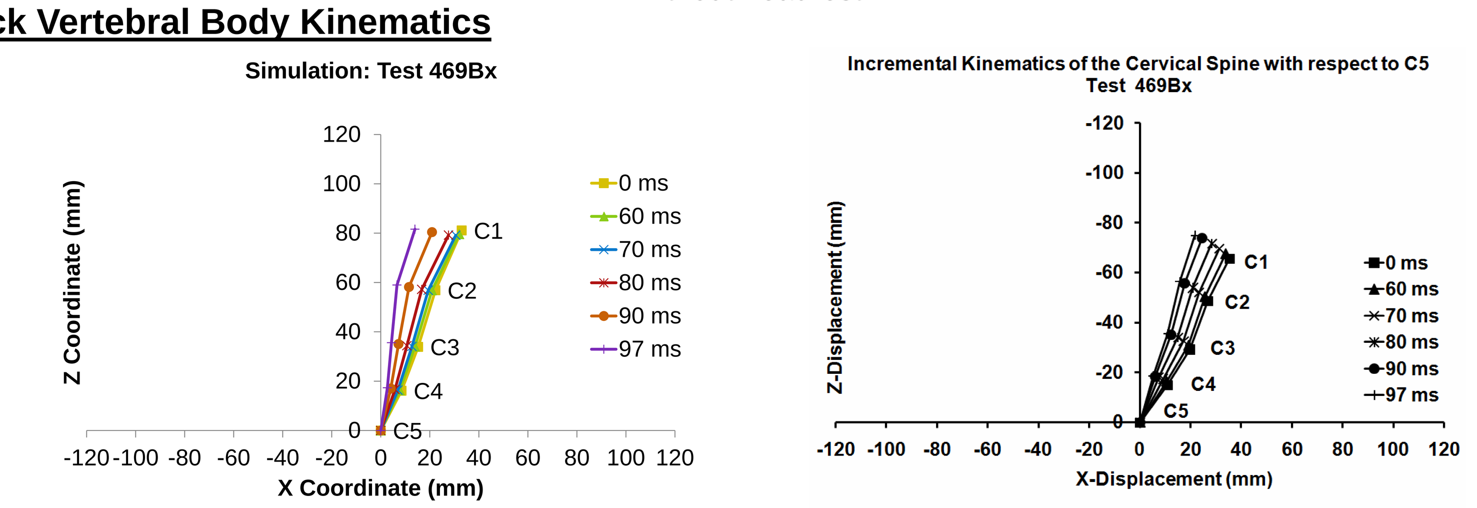

Fig. 12: Neck vertebral body kinematics with headrest

Facet Strain

- The FE model predicted maximum stretch ratios for various facet joints (Fig.13).
- C2-C3 facet experienced the highest deformation than the rest of the joints.
- It appears that the degree of stretch was associated with amount of compression experienced by the facet joints.

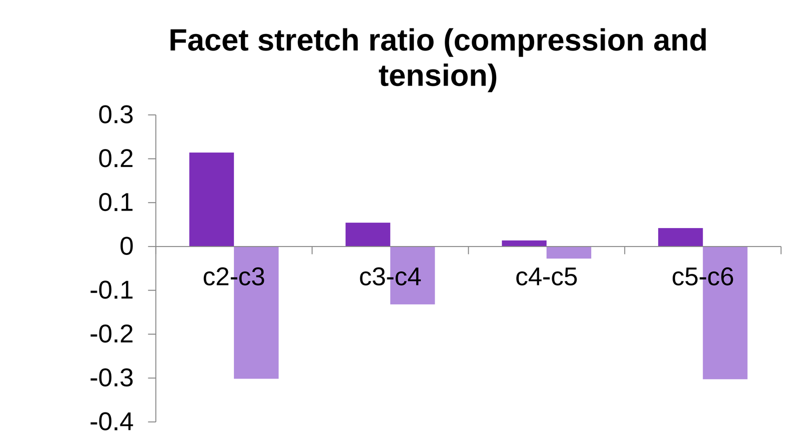

Fig. 13: Maximum facet stretch ratio at various facet joints

DISCUSSION / CONCLUSIONS

- An anatomically detailed FE neck model was developed using solid blocking technique in which the block can be used for the mesh generation for a new cervical geometry to save meshing cost
- The integrated neck and head complex was validated against the head-neck responses in cadaveric drop tests and showed good biofidelity as assessed by the CORA rating method
- The model matched neck vertebral body kinematics data in cadaveric rear-end impact experiments. And the head displacement had a fair correlation with experimental results
- C2-C3 facet experienced the highest deformation

Though the model-predicted internal response variables began to assist in improving our understanding of the local phenomena associated with spine kinematics, further validation of the model against experimental data is needed. Future study will also include use data from volunteer tests and simulate neck responses in frontal impact conditions. The determination of the relationship between the resulting facet strain and associated neck kinematics will help provide the design basis to improve head-restraint system thereby reducing and mitigating neck injury.

ACKNOWLEDGMENT

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