DEVELOPMENT AND VALIDATION OF A HEAD-NECK FINITE ELEMENT MODEL FOR INJURY ANALYSIS

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In this study, the digitized geometrical data of the embalmed skull and vertebrae (C1-C7) of a 68 year-old male cadaver were processed to develop a comprehensive, geometrically accurate, nonlinear C0-C7 FE model. The biomechanical response of human neck under near vertex drop impact conditions were investigated and compared with the published experimental data. The results show that the predicted resultant head impact force history and corresponding motions of each motion segment all agree well with published data. The stress variation histories in the neck were found to be consistent with the rotational motions of the motion segments under dynamic loading. The current model may offer potential to effectively reflect the behavior of human cervical spine suitable for further biomechanics and traumatic studies.

KEY WORDS: Finite Element, Cervical Spine, Biomechanics, Injury, Impact

INTRODUCTION: The cervical spine or neck is the most mobile region and a frequent site of injury in the human spine. Injuries in this region caused by drastic impact during sports or diving are very important because they are often associated with spinal cord injuries, which can be devastating or life threatening. Biomechanical models, such as *in vitro* models, *in vivo* models, and finite element (FE) models are helpful in the understanding of the underlying mechanisms of injury and dysfunction, leading to improved prevention, diagnosis, and treatment of clinical problems. With the invention of powerful computational capabilities, FE models are widely used as a tool for various biomedical applications. FE models often provide estimates of parameters that *in vitro* or *in vivo* experimental studies either cannot, or difficult to obtain, accurately. The results from FE models can also suggest crucial experiments that should be undertaken. In the current study, a detailed three-dimensional nonlinear C0-C7 FE model was developed. The predicted biomechanical response of human neck under near vertex drop impact condition were analyzed and compared with published experimental data to justify the validity of our C0-C7 FE model for future biomedical and traumatic studies.

METHODS: An embalmed cadaveric spinal column of skull (C0) and C1 to C7, free from any physical abnormalities, of a 68 year-old male obtained from Singapore General Hospital was used for the development of the FE model. A flexible 6 degrees of freedom digitizer was used to extract the surface profile of the bony structures (skull, C1-C7). The automatically registered data of the surface profile represented as point-clouds were subsequently processed using surface modeling software (Surfacer 7.0), to create the sequential cross section outline of the vertebra. These geometrical boundary data files were then imported into ANSYS 6.0 for the three-dimensional solid volume and mesh reconstruction using a bottom-up approach. The detailed process of digitization and generation of the bony skull and vertebrae mesh models are described elsewhere (Ng and Teo, 2001).
The geometry of bony structures was obtained from the dry embalmed specimen, the geometrical data of the associate ligaments and intervertebral discs based on the information obtained from literature (Gilad and Nissan, 1986; Shirazi et al., 1984). All of the important components such as cortical bone, cancellous bone, posterior elements, disc annulus, disc nucleus, and endplate were modeled for each motion segment. The completed C0-C7 FE model was configured to contain a lordosis of about 37 degrees, which is consistent with the neck posture of a seated 50th percentile male (Linder, 2000) (0). The major ligament groups associated with the cervical spine and important for the neck movement were incorporated.

The cross-section areas used were average values reported previously, and their attachment points were chosen with great care to mimic anatomical observations as closely as possible (Goel and Clausen, 1998; Yoganandan et al., 2000).

The modeling, meshing and analysis were performed in ANSYS 6.0 and LS-Dyna. The vertebrae, discs and endplates were meshed by eight-node "brick" elements. The skull was meshed using four-node shell element. The ligaments were modeled using nonlinear link elements, which only permit tensile axial force transmission to simulate the mechanical behaviour of human ligaments. Furthermore, surface to surface contact elements were employed to model fourteen joint articulations through C1 to C7: 6 left and 6 right facet joints through C1 to C7, dental-atlantal joint, and transverse ligament-odontoid process articulation. 0 shows the final C0-C7 FE model consists of 21,765 elements and 29,066 nodes and the global XYZ coordinate system.

The material properties of the elements representing the skull and vertebrae were assumed to be elastic and perfectly plastic, homogenous and isotropic. To simulate the failure property of the vertebrae, a failure strain of 1%, which is appropriate for the compact bone was assigned to all the hard tissues (Gibson and Ashby, 1997). In addition, the hourglass coefficient of 0.1 was used to minimize hourglass energy for the disc and endplate. The materials of ligaments and densities for various materials were derived from literatures (Deng and Goldsmith, 1987; Lee et al., 2000). Furthermore, mass elements were added to nodes close to the c.g. of head in the mid-sagittal plane of the skull model to simulate a head mass of 4.4 kg and its moment of inertia of 0.0235 kgm^2 (Camacho et al., 1999).

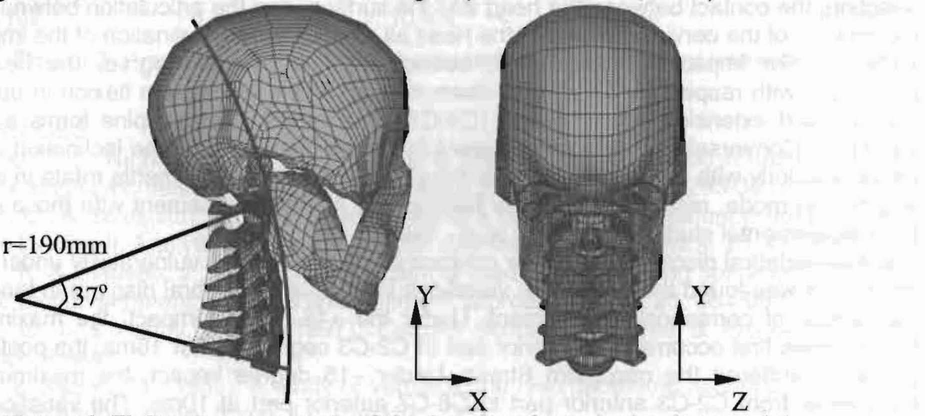


Figure 1 Finite element mesh of the head and cervical spine model.

As validation is crucial for further use of the FE model for other analyses, the current C0-C7 FE model was analyzed under near vertex drop impact condition and compared with results published in literature (Camacho et al., 1999). Accordingly, the model configured upside-down 1 mm above a lubricated rigid surface was given an initial downward velocity and acceleration of 3.2 m/s and 9.81 m/s^2, respectively. The inferior surface of C7 was restricted to move only in vertical direction. A mass of 16kg was added at the inferior surface of C7 vertebral body to simulate the experimental setting. The responses of the head-neck complex with the rigid impact surface at the angle of +15 and −15 degrees were compared against the experimental corridors (Camacho et al., 1999).

RESULTS AND DISCUSSION: 0 shows the comparisons between the predicted resultant head impact force history and those measured from experiments (Camacho et al., 1999). For the two impact angles (-15 and +15 degree), the model produced force histories correlate well with experimental data. The peak head force occurred immediately (within 2ms) after the impact of head on the surface. The vertical load exerted by the torso mass and the simultaneous non-uniform deformation of the intervertebral discs resulted in the oscillation of the head force after the first impact. The out of range data compared with the experimental corridor should be due to the assumed material.

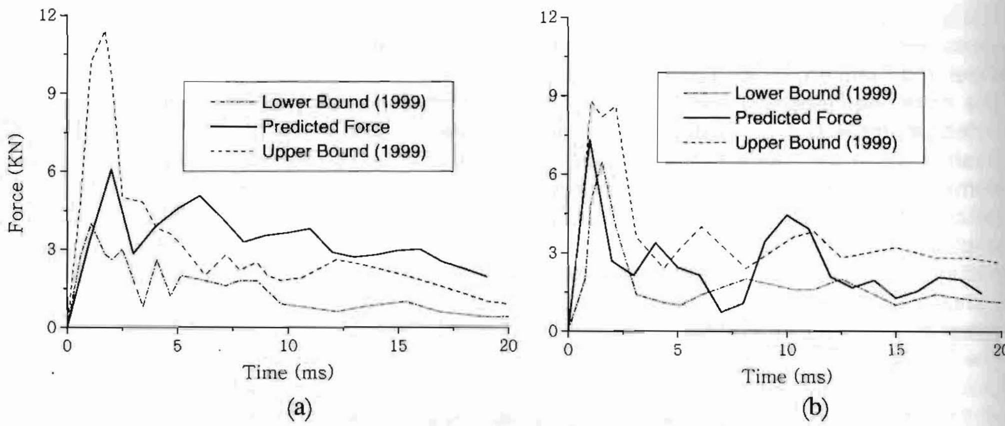
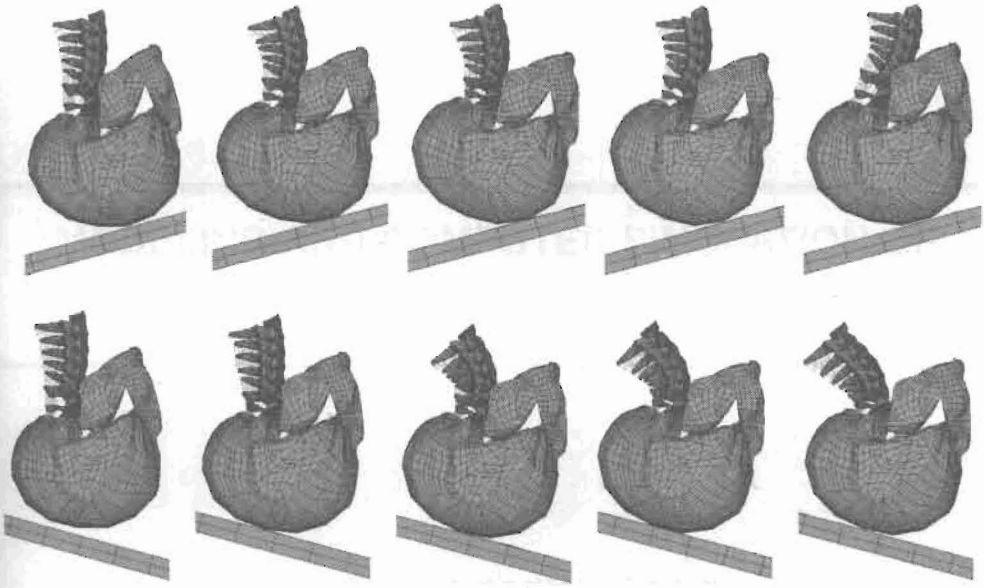


Figure 2 Comparison of predicted resultant head impact force history against experimental data (from Camacho et al., 1999). (a) The impact orientation at –15 degree (b) The impact orientation at +15 degree.

0 shows the immediate responses of the head-neck complex during the first 20 ms after the near-vertex impact with rigid surface. As C7 was restricted to move only in the vertical direction, the contact between the head and the surface, and the articulation between C0-C7, the rotation of the cervical spine and the head all depend on the inclination of the impact rigid surface. For impacting toward rigid surface inclined at +15 degree, the head move posteriorly with respect to C7 without much rotation finally resulting in flexion in upper level (C0-C3) and extension in lower level (C3-C7). The whole cervical spine forms a S-shape curvature. Conversely, for impacting toward rigid surface of –15 degree inclination, the head move anteriorly with respect to C7 while the C0-C5 and C5-C7 segments rotate in extension and flexion mode, respectively. These findings are in close agreement with those observed from experimental studies (Camacho et al., 1999).
The intervertebral discs are the major concern of injury due to its vulnerability under dynamic impacts. It was found that the stress variations in each intervertebral disc are in tandem with the motion of corresponding segment. Under the +15 degree impact, the maximum Von Mises stress first occurred in posterior part of C2-C3 segment, after 16ms, the posterior part of C6-C7 suffered the maximum Stress. Under –15 degree impact, the maximum stress transferred from C2-C3 anterior part to C6-C7 anterior part at 10ms. The variations of the maximum stress distributions in disc are consistent with those of the relative rotational angels of moment segments. It is implied that with the peak rotational values, it is possible to determine the location and direction of potential injury in the neck during dynamic impact.

CONCLUSIONS: A comprehensive, geometrically accurate, nonlinear FE model of head and cervical spine has been developed. The validation shows that the motion values predicted from current FE model under near vertex drop impact conditions agree well with the experimental data. The model can effectively reflect the behaviour of human cervical spine and is therefore suitable for further traumatic studies. The stress variation histories in the neck were consistent with the rotational motions of the motion segments under dynamic loading. The corresponding maximum rotation angle of the each motion segment may help to determine the potential injury to cervical spine under dynamic conditions.



0 ms 5 ms 10 ms 15 ms 20 ms

Figure 3 Predicted response of the neck in the near-vertex impact.

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