FE ANALYSIS OF HEAD-NECK RESPONSES DURING WHIPLASH

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Abstract:A detailed three-dimensional head-neck (C0-C7) finite element (FE) model was developed based on the actual geometry of a cadaveric specimen and used to characterize the whiplash phenomenon of the head-neck region during rear-end collision. A maximum rear impact pulse of 8.5G of acceleration, simulating about 20mile/hour rear-end collision, was applied to C7. The effects of headrest on the responses of head-neck complex were also discussed. The study demonstrates the effectiveness of the current C0-C7 FE model in characterizing the gross responses of human cervical spine under whiplash conditions. During whiplash, the lower cervical levels, especially the C6-C7, experience higher extension motion in the acceleration/decerleration syndrome of the neck, suggesting that the whole cervical spine is at risk of extension injuries than flexion injuries. Also the use of a proper headrest can effectively reduce the cervical spine from extension injury during the acceleration phase of cervical spine in whiplash.

Key words: Finite element, Rear-end impact, Cervical spine, Whiplash, Biomechanics

1. Introduction

In passenger vehicular accidents, an 8-mile/hour rear-end collision produced a 2G acceleration of the vehicle and a 5G acceleration of the head with a span of 300ms or less [1]. Whiplash is the common occurrence during which the cervical spine is frequently injured. The whiplash injuries as a result of the cervical acceleration/deceleration syndrome within this span of short duration are often dangerous and often associated with spinal cord injuries, which can be devastating or even life threatening. It is therefore important to understand the underlying mechanisms of this kind of injury and dysfunction, leading to improved prevention, diagnosis, and treatment. Accordingly, in current study, a detailed three-dimensional FE model of the whole head-neck complex developed previously was used to investigate the biomechanical responses of the head and cervical spine with and without the headrest during whiplash.

2. Methods

A 3-d FE model of the C0-C7 was developed based on the method previously reported [1][3]. Briefly, the 3-d FE model of the head and cervical vertebrae were developed with geometrical data based on the actual geometry of a 68 year-old male cadaver specimen. The surface profile of the bony structures (head, C0-C7 vertebrae) was captured using a flexible digitizer. The digitized coordinates of the surface profile were automatically registered in the system and were subsequently processed for the FE mesh generation. For the modeling of the intervertebral discs (IVDs), the basic geometries taken from the average values reported in literature [4] were used. Furthermore, the major ligaments and muscle groups associated with the cervical spine were also incorporated in the model, for which the attachment points were determined from anatomic text [5]. Figure 1 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

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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 [6][7]. For the muscles, the cross section and initial length of various muscle groups were derived from Deng and Goldsmith[8]. In addition, due to the lack of available date, only passive effects of muscle materials were considered, the Young's modulus of SternoCleidoMastoid obtained by Yamada[9] was assigned to all the muscle groups. Furthermore, some mass elements were added to certain nodes lying along the mid-sagittal plane of the head to simulate head mass of 5.5 kg and moment of inertia of 0.035 kgm2, comparable to those of experimental specimens[10].

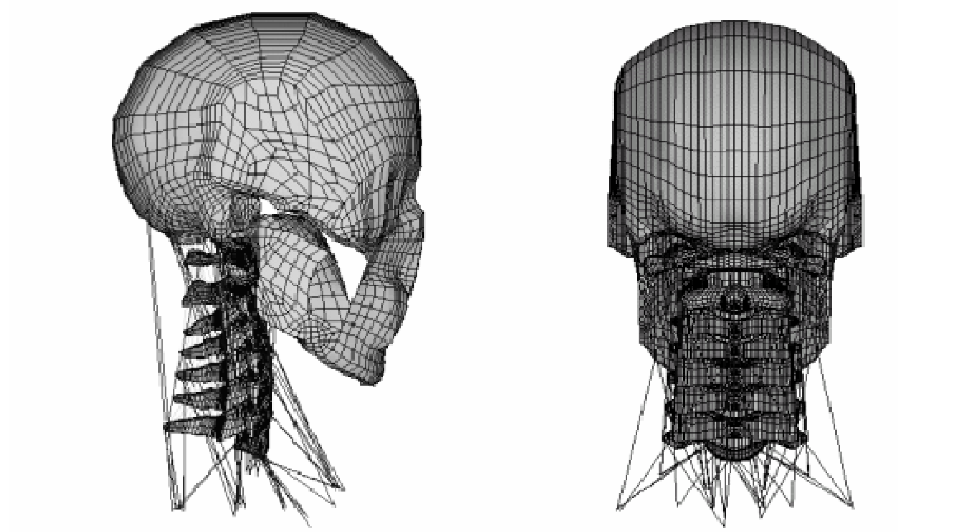

Figure 1. Finite element mesh of the head and cervical spine model under lateral and posterior view

For the whiplash study, to simulate about 20mile/hour of rear-end collision, a horizontal acceleration along the X-axis with peak value of 8.5G, onset rate of 170G·s-1 and duration of 100ms followed by slower deceleration (Figure 2) was applied on the inferior surface of C7 vertebral body. To investigate the effect of headrest on the response of head and neck during whiplash, an addition analysis was carried out by introducing a foam plate at an angle of 45° and 100mm away from the head.

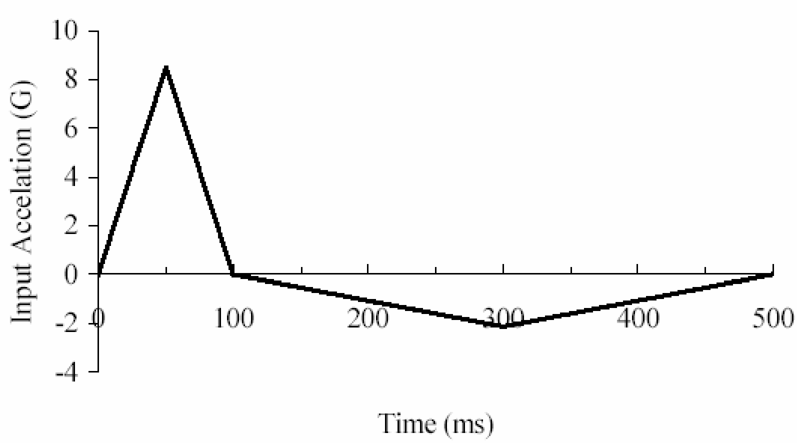

Figure 2. Input acceleration on C7 for whiplash simulation

3. Results

Figure 3 shows the predicted variation of rotational angles of each motion segment during whiplash without head restraint. During the first 10ms after impact, all the motion segments, except C6-C7, were in flexion. After that, the lower segments (between C3 to C6) turned to extension motion with different angulations while the upper segments (between C0 to C3) maintained the flexion motion for much longer duration before turning to extension motion. During the 20-70ms period, the whole C0-C7 structure formed a S-shaped curvature with flexion at the upper levels and extension at the lower levels. After that, all the motion segments went into extension and the entire cervical spine formed a C-shaped curvature. After C7 reached its peak velocity value at 100ms and began to decelerate, the extension angular rotations of most motion segments began to decrease as well. In this cervical acceleration/deceleration syndrome (with 200ms duration), all the motion segments experienced higher peak extension rotation than flexion rotation. The C6-C7 segment experienced much higher extension angles (about 18_{o}) as compared against its physiological range[10] of 8 $_{o}$, implying a higher potential of injury at this segment.

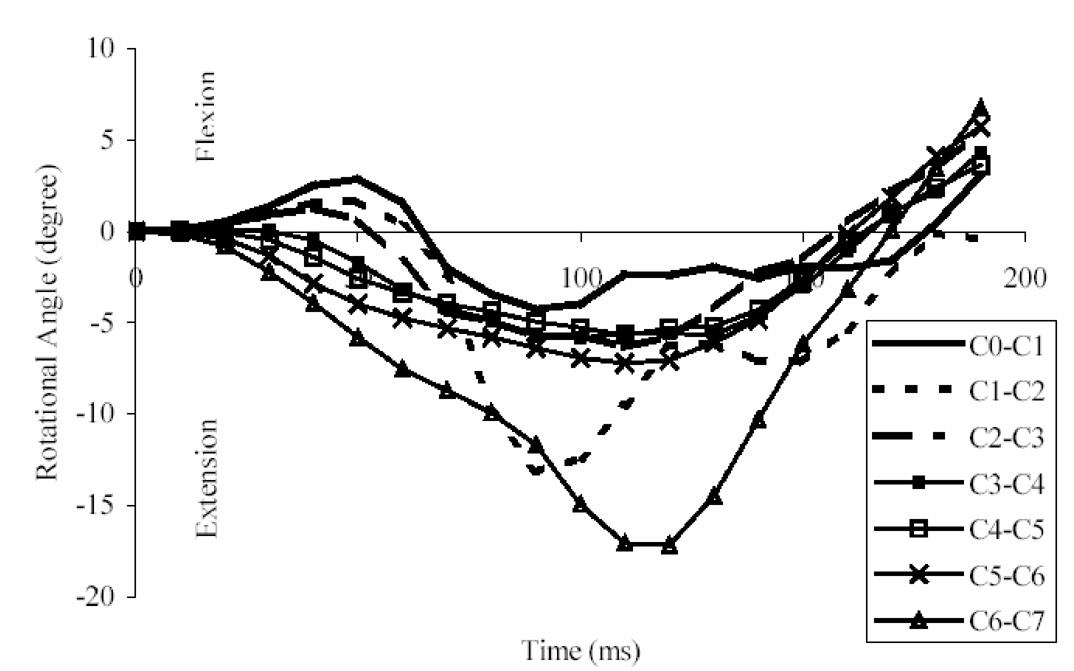

Figure 3. Predicted rotational angles of each motion segment during whiplash (without headrest)

The intervertebral discs are the most vulnerable portions to be injured under dynamic conditions. Figure 4 shows the variation of the maximum Von Mises stress in the C6-C7 disc during whiplash. The stress variation is in tendon with the motion of segment. During the acceleration stage, the maximum stress increased with increasing extension rotational angle and peaked at around 110 ms, and reduced in the deceleration stage subsequently. The variations of the maximum stress in all cervical intervertebral discs follow the same trend. The C0-C7 FE model predicted much higher peak stress at C6-C7 disc at most time because of its highest rotational angle during whiplash. 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 whiplash.

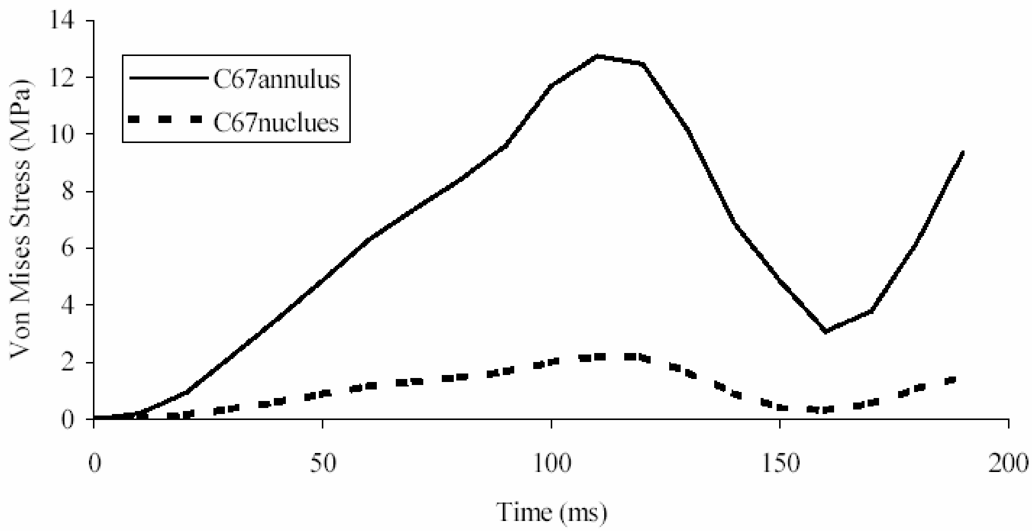

Figure 4. Predicted maximum stress history of C6-C7 disc during whiplash (without headrest)

The effect of headrest on the response of neck during impact is obvious. At around 80ms, the head collided with the headrest preventing the continual extension motion. Between 80-100ms, the extension motion was reduced, then increase in extension rotation form 100-120ms. The acceleration/deceleration syndrome from time 100ms onwards was considered as secondary whiplash. As shown in Figure 5 and Figure 6, the peak extensional angle of C6-C7 segment and the peak maximum stress in C6-C7 annulus were reduced by 28.5% and 25.9%, respectively. The comparison of other motion segments showed similar trend.

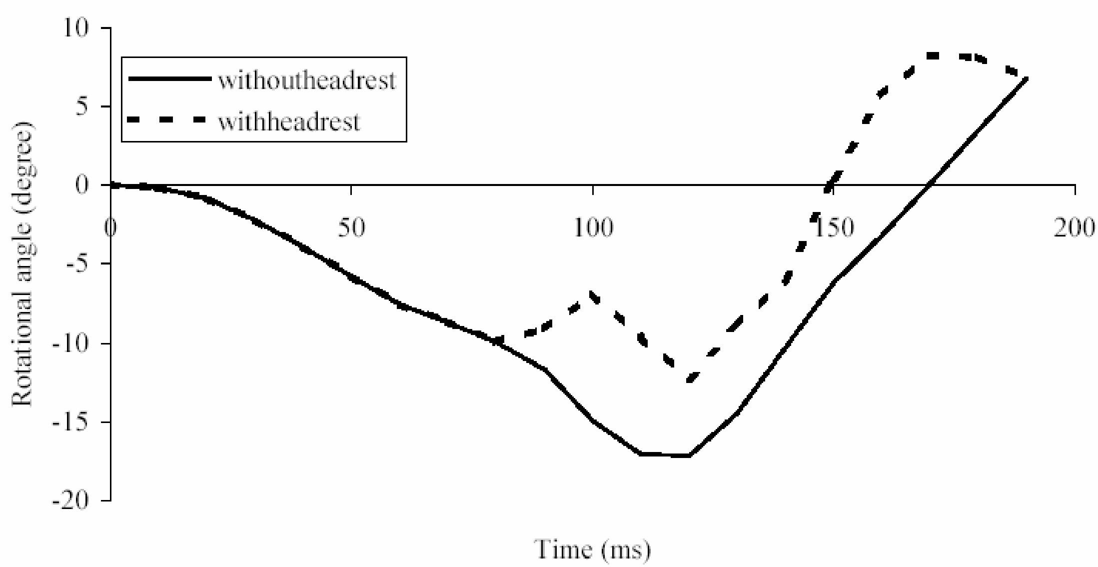

Figure 5. Effect of headrest on the rotation of C6-C7 segment during whiplash (with headrest)

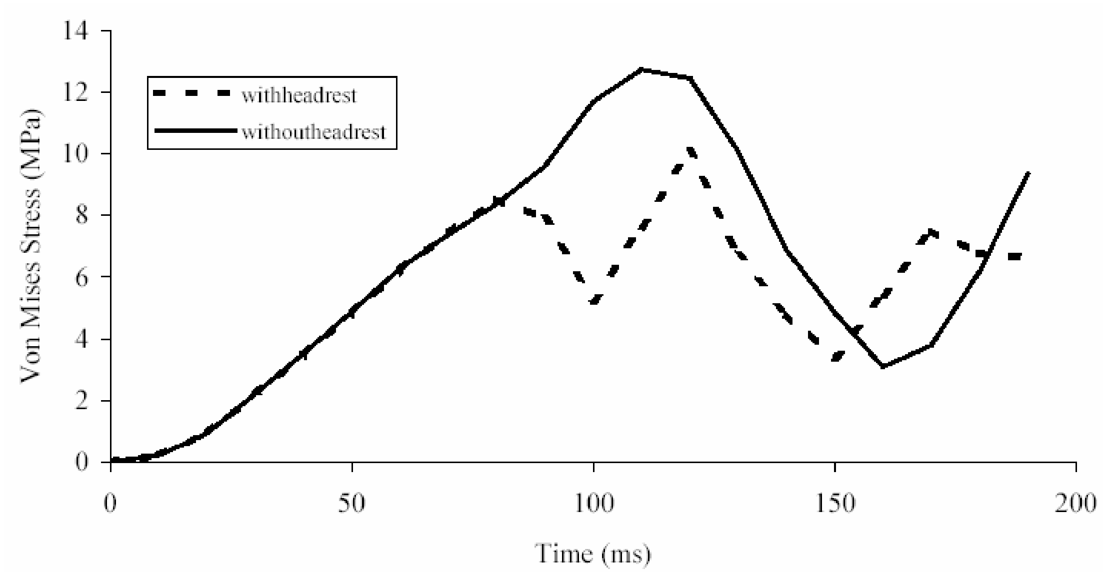

Figure 6. Effect of headrest on the stress history of C6-C7 disc during whiplash (with headrest)

4. Discussion

In the current study, a detailed 3-dimensional C0-C7 FE model was developed and used to investigate the response of the whole head-neck complex under whiplash conditions. The results showed that the predicted variations of rotation angles at different levels of the motion segments are well compatible with the experimental finding[10][11]. During 20-70ms period, the neck formed a S-shaped curvature, which was clearly observed in experiments. After 70ms, the whole cervical spine went into extension motions, forming a C-shape curvature, and the angular motions of most segments were beyond the physiological range of motion, suggesting that during whiplash (the cervical acceleration/deceleration syndrome), the whole cervical spine are likely at risk of extension injuries rather than flexion injuries. This was illustrated at the lower levels, especially C6-C7, may experience hyperextension in the early phase due to high acceleration of C7. Therefore the lower cervical spine levels (C3-C7) could be a potential area to be in high risk of extension injuries during whiplash. Although the absolute peak values of each motion segment may be exaggerated compared to the actual crash environment due to the restriction of rotation of C7, the relative motions among the cervical spine should not be affected.

The headrest was found important to reduce the extension injury risk during whiplash. The secondary whiplash produced after the impact of the headrest could increase the risk of the victim hitting the steering wheel or dashboard in shorter time than without headrest. Also the extension angles under both primary and secondary whiplash phases are greater than the physiological range of flexion angles, the head-neck is under greater extension risk in whiplash injuries. In the current study, the initial distance between the head and headrest was assumed to be 100mm. Garcia and Ravani[12] investigated the effect of distance on the S-shaped kinematics during whiplash. They reported that if the distance was less than 50mm, the cervical spine even would not form an S-shape curvature. Furthermore, since the inclination of headrest can affect the position of the impact contact between the head and the headrest, it will influence the motions of the neck after impact. This study illustrates the incorporation of headrest reduce the extension rotation of the neck during whiplash.

5. Conclusions

We have successfully used the C0-C7 FE model to characterize the post responses of the head-neck simulating an 20-mile/hour rear-end collision. The S- and C-curvatures of the spine are predicted and are in close agreement with reported literatures of rear-end collision investigations.

During whiplash, the lower cervical levels, especially the C6-C7, may experience hyperextension in the early acceleration phase of C7. The lower levels could be a high risk potential area during whiplash. The whole cervical spine is likely at risk of extension injuries than flexion injuries in whiplash. The use of headrest can also help to reduce the extension rotation of the neck during whiplash.

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