Does a neck segment exhibit the same vulnerability under various impact conditions?

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Keywords: cervical spine; trauma; impact velocity; finite element simulation

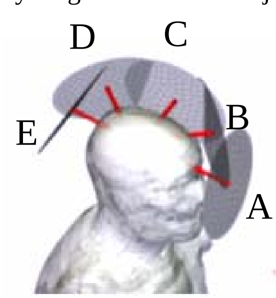
Abstract: In pedestrian, cyclist and motorcyclist accidents, cervical spine injuries are often observed, with complex mechanisms occurring for multidirectional loadings. In this work, finite element analysis was used to predict the injury chronology and specific injured components of the cervical spine segment. Simulations of five different impact directions (frontal, lateral, rear, frontal oblique, rear oblique) were analyzed with an initial velocity of 5 m/s and 7 m/s. The first injuries recorded were ligament ruptures of the upper cervical spine and bone fractures of the lower cervical spine. Comparing these simulation results, the injuries under flexion mechanisms seem to be less severe than with extension or coupled kinematics.

1 Introduction

The cervical spine segment is a very complex and mobile structure of the human body [1]. Once a trauma situation occurs, the head-neck segment is highly loaded, leading to severe trauma with a lethal or permanent incapacity risk. The cervical spine was largely studied for its mechanical properties during a frontal impact to investigate whiplash mechanisms [2, 3]. For pedestrian, cyclist and motorcyclist accidents, the head-neck segment is loaded under various impact directions. How do these impact directions affect injury mechanisms, potential injuries and their severity? Can different kinematics and injuries to the neck segment be observed at various impact velocities? To answer these questions, finite element simulations [4] could be a valuable tool. By simulating frontal, lateral, rear and oblique dynamic loadings on the HUMOS head-neck segment, this numerical study showed an area of weakness on the spinal segment whatever the impact condition.

2 Material and Methods

The model used was the HUMOS head-neck segment under loading conditions relevant to those used for model validation [4]. For test convenience, the lower thorax, abdomen, lower and upper limbs were removed. The upper thorax component was set as a rigid body and fixed. As no investigations were performed on the head segment, it was set as a rigid body. The test consisted of a 75-kg circular plate (to include the inertial effects on the whole body) with an initial velocity of 5 m/s and 7 m/s. Five loading conditions, from frontal impact to rear impact, were investigated (cf. Figure 1). The simulations were recorded for 40 ms at 5 m/s and 30 ms at 7 m/s. One major interest in human modeling lies in the possibility of recording specific parameters which cannot be recorded during experiments. The numerical injury identifications are thus assessed through the combined analysis of joint kinematics (to identify pathological movement [5]); the Von Mises level was assumed as an indicator for bone fracture (130 MPa and 50 MPa for compact and spongious bone, respectively); and strain level to investigate the potential ligament failure risk according to the work by Yogonandan and Panjabi [4, 6, 7].



A: frontal
B: frontal oblique
C: lateral
D: rear oblique
E: rear

Figure 1: Illustration of the five impact configurations

3 Results

Head-neck segment kinematics:

In the frontal impact direction, the head segment exhibited translation kinematics perpendicular to the impactor plane from 0 ms to 14 ms. The neck segment showed extension kinematics. From 14 ms, the entire head-neck segment exhibited hyperextension kinematics. At the end, the upper cervical spine exhibited dilatation processes.

In the lateral impact direction, the head-neck segment showed lateral rotation whereas the upper and lower cervical spine exhibited local rotation.

In the rear impact direction, from 0 ms to 10 ms, the head segment exhibited translating kinematics in the direction of impact velocity, inducing homogeneous flexion kinematics for the cervical spine. After 10 ms, hyperflexion kinematics were observed on the entire head-neck segment.

In the frontal oblique and rear oblique impact direction, the head-neck segment showed coupled lateral flexion (extension) and torsion effects homogenously distributed along the cervical spine.

At the 7 m/s velocity, mechanisms similar to those reported before were observed. The major differences were reported in the time for the different steps of cervical spine kinematics. Notably, while the lower cervical spine exhibits the same amplitude for rotations, the upper cervical spine exhibits an increased rotation level, which may correlate with higher injury risk.

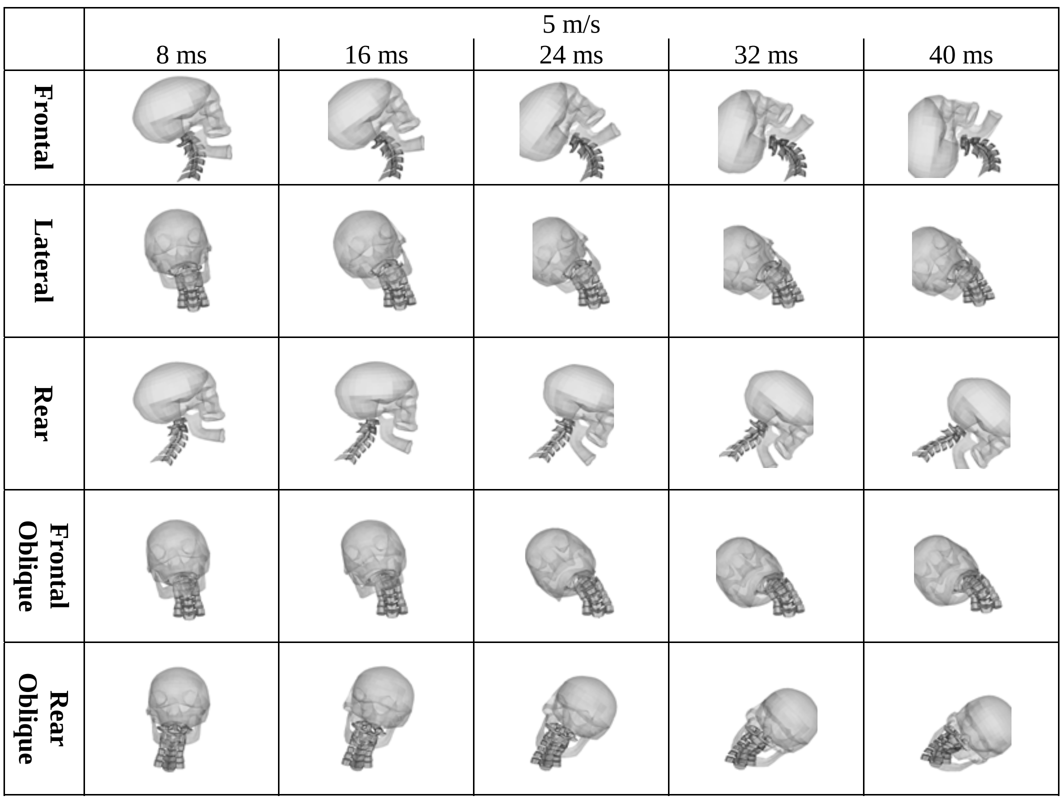


Table 1: Head-neck segment kinematics for the five impact configurations at 5 m/s of initial impact velocity

Virtual trauma:

In the frontal impact direction, the lower cervical region, i.e. around C4-C6, was highly recruited, leading to potential bone failure translating from C6 to C5 and C4. The upper cervical component, C0-C2, also exhibits potential failure of the anterior longitudinal ligament due to hyperextension effects.

The lateral impact first showed potential bone fracture for the lower cervical spine structure, with C6 bone fracture to C5, C4 and C3. Local rotation on C0-C2 induced potential failure of the apical ligament.

The rear impact showed potential simultaneous bone failure on C6 and C5. The interspinous ligament was assumed to reach its ultimate threshold on C1-C2.

The frontal oblique impact led us to postulate severe trauma, probably induced by the combination of lateral and frontal extension. The lower cervical spine showed fractures from the C6 to C3 spine units. Ligament failures were postulated on the upper cervical spine, mainly with the apical ligament on C0-C2.

The rear oblique impact exhibited the same combination of effects as in the previous case: potential injury of the interspinous ligament on C0-C2. Potential C6 and C5 bone failure was observed.

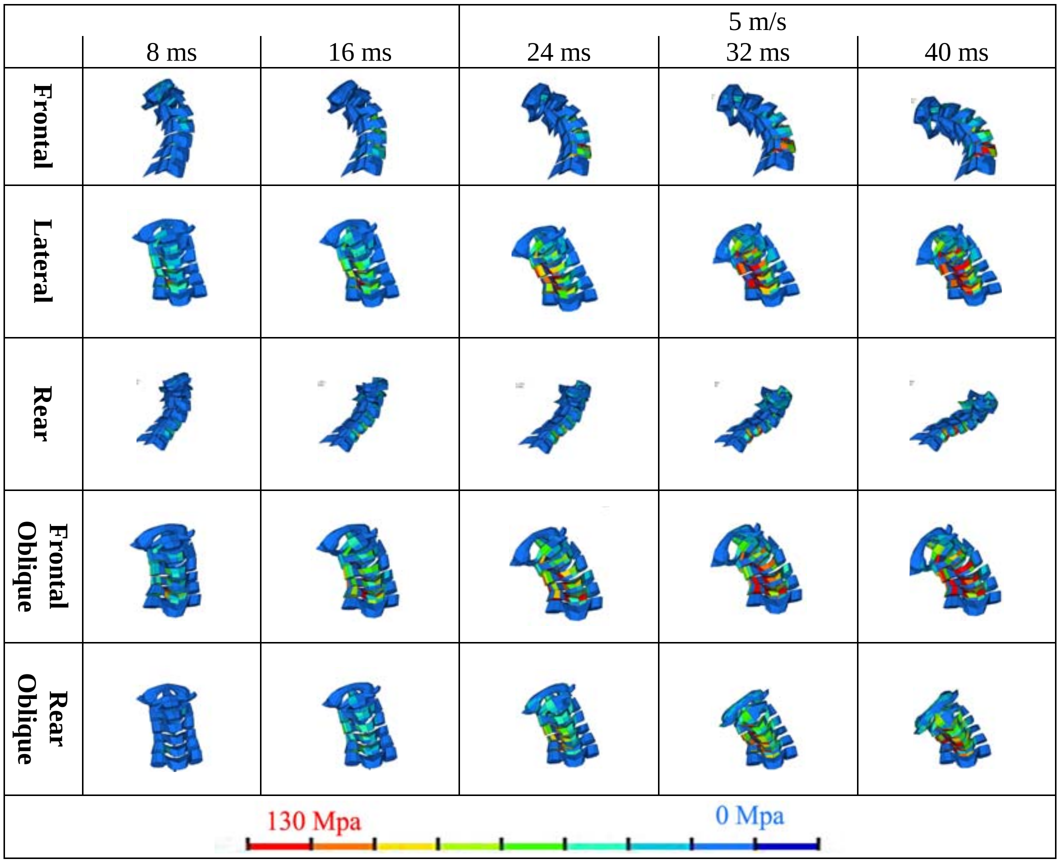


Table 2 Von Mises stress on the cervical vertebrae for the five impact configurations at 5 m/s of initial velocity

The rear oblique impact exhibited a combination of flexion and torsion effects leading to potential C6 and C5 failure.

At the 7 m/s velocity:

The frontal impact showed potential bone failure on C6 and C5. Note that there is no bone failure recorded on C4. The anterior longitudinal ligament of the upper cervical spine segment was highly recruited up to its potential failure level.

The lateral impact exhibited a similar injury chronology as at the 5 m/s velocity with fracture on C6, C5, C4 and C3. A potential failure of the apical ligament on C0-C2 was postulated.

The rear impact led to hyperflexion kinematics with potential C6 and C5 failure. Local rotation on C1-C2 induced potential failure of the interspinous ligament.

The frontal oblique impact showed the same mechanisms as with the previous velocity. Potential failure of the lower cervical spine was observed on

C6 to C3. Potential failure of the apical ligament was observed.

The rear oblique impact exhibited a combination of flexion and torsion effects leading to potential failure on C6 and C5.

4 Conclusions – Discussion

In frontal impact, for the same position of the impactor, the lower cervical spine showed the same kinematic level, whereas the upper cervical structure exhibited an increased range of mobility compatible with the S-shape effects described for whiplash trauma [4]. This increased mobility could have a strong incidence on injury risk (bone fracture, ligaments injuries).

The simulations performed in these studies exhibited potential injuries of the upper and the lower cervical spine. Bone fractures were essentially recorded from C6 to C4 in the frontal, lateral and frontal oblique impact simulations. Ligament injuries were mainly recorded on the upper cervical spine in the lateral, frontal oblique and rear oblique impact simulations. While the injury chronology showed large dispersion (Table 3), the injuries observed under flexion mechanisms were less severe than under extension and coupled kinematics. It seems that these potential failures were observed with similar head-neck segment kinematics. The velocity could not influence the potential injuries according to the risk of bone fracture. Additionally, velocity has an incidence on potential injuries of the upper cervical spine, with higher amplitudes recorded. If fused areas could be clearly established on the upper and lower cervical spine, wider investigations are needed to promote new injury criteria for the neck segment. Such investigations could also be followed by significant improvements in the model to properly describe fracture processes.

Impact	1st injury	2nd injury	3rd injury
Frontal	ALL at C1-2	C6	C5
Lateral	C6	C1-2	C5&CLR&LF at C5-6
Rear	ISL at C1-2	PLL	LF at C4-6
Frontal oblique	C6	C5&AL	C4&AlarLig
Rear oblique	ISL at C1-2	C5	ISL at C2-3

Table 3: Injury chronology in these tests

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