

Simultaneous Three-Dimensional Analysis of Cervical Spine Kinematics in the Axial and Sagittal Views during a Simulated Frontal Impact: Differences between Tensed and Relaxed States

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Study Design: Prospective experimental study on humans.

Purpose: To determine whether postural differences during a low-speed impact are observed in the sagittal and axial views, particularly in a relaxed state.

Overview of Literature: Three-dimensional motion capture systems have been used to analyze posture and head-neck-torso kinematics in humans during a simulated low-speed impact, yet little research has focused on the axial view. Since a seatbelt asymmetrically stabilizes a driver's right shoulder and left lower waist into the seat, it potentially creates movement in the axial view.

Methods: Three healthy adult men participated in the experimental series, which used a low-speed sled system. The acceleration pulse created a full sine shape with a maximum acceleration of 8.0 m/s² at 500 ms, during which the kinematics were evaluated in relaxed and tensed states. The three-dimensional motion capture system used eight markers to record and analyze body movement and head-neck-torso kinematics in the sagittal and axial views during the low-speed impact. Head and trunk rotation angles were also calculated.

Results: Larger movements were observed in the relaxed than in the tensed state in the sagittal view. The cervical and thoracic spine flexed and extended, respectively, in the relaxed state. In the axial view, larger movements were also observed in the relaxed state than in the tensed state, and the left shoulder rotated.

Conclusions: During simulated frontal impact, the rotation angle between the head and trunk was significantly larger in the relaxed state. Therefore, we recommend also observing movement in the axial view during impact tests.

Keywords: Spine; Biomechanical phenomena; Imaging, three-dimensional

Introduction

Cervical injuries caused by traffic accidents are commonly

reported and include cervical sprain, cervical spinal cord injuries, cervical spine fractures, and dislocation [1]. Since one-third of these injuries occur in front impact collisions

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[2], evaluating the kinematics of these collisions is considered clinically important. An evaluation of the flexion-extension motion of the cervical spine in a low-impact test of whiplash loading was previously conducted, because this is considered an important injury mechanism [3]. However, rotation of the cervical spine is regarded as an important factor for determining the mechanisms underlying cervical spine injuries, such as that reported for fractural dislocation of the vertebral facet in a traffic crash [4,5]. Although rotation of the cervical vertebrae upon impact has been reported in human subjects postmortem and in a dummy model [6], we are not aware of any published reports on experiments with human subjects.

Recent experiments using a safety support device or autonomous emergency braking (AEB) to assist the driver's ability to acknowledge, judge, and operate a car indicate that damage can be reduced and impacts can be lighter [7]. Moreover, when AEB operates to prevent a vehicle collision, the driver's posture automatically changes [8,9]. Therefore, differences in muscle response and posture are expected based on the driver's awareness of the danger prior to a collision. Although experiments have been conducted to evaluate changes in the driver's posture during frontal impact [10-23], analyses of three-dimensional (3D) kinematics of the occupant in the sagittal and axial views in human experiments are limited [10,17,18,22,23].

Several studies have indicated that cervical spine motion is important for head-neck-torso kinematics [24,25]. Therefore, we examined the head-neck-torso kinematics to evaluate cervical spine motion.

We hypothesized that significantly greater movement of the participant's kinematics occurs in a relaxed state than in a tensed state, not only in the sagittal view but also in the axial view. The present study aimed to test this hypothesis by analyzing the occupant's posture and head-neck-torso kinematics in the sagittal and axial views during a low-speed impact using a 3D motion capture system.

Materials and Methods

1. Subjects

Three healthy male volunteers agreed to participate in the experiments. Their average age was 23 years (range, 22–24 years), average height was 170.3 cm (range, 168–173 cm), and average weight was 68.5 kg (range, 64.3–75.3 kg). The

experimental protocol, which complied with the Declaration of Helsinki, was reviewed and approved by the Ethics Committee of our university, and all the volunteers provided informed consent.

2. Experimental protocol

The effect of muscle activity on physical movement in a pre-impact braking situation and determination of any differences between tensed and relaxed states relied on prior methodologies [12]. Under both conditions, the volunteers wore a tight-fitting bodysuit with markers, surface electromyographs were adhered using double-sided tape, and the volunteers sat on a low-speed sled system. In the relaxed state condition, the volunteers were asked to keep their muscles relaxed during the impact until the motion of the body was stopped by the seatbelt. In the tensed state condition, the volunteers were asked to tense all of their muscles and to brace against the anticipated acceleration. Muscle activity was measured using surface EMG to determine whether the muscles were in the desired state.

Each condition was performed twice for each volunteer, with the experiment starting suddenly in the relaxed state condition and following a countdown in the tensed state condition.

3. Experimental set-up

A low-speed sled system that could simulate a frontal impact was used (Fig. 1) [12]. The sled system generates acceleration similar to the power of real braking when an AEB system activates in an emergency. It is equipped with a vehicle seat, three-point seatbelt, and footplate. The seatbelt fixes the driver's right shoulder and left lower waist into the seat. In order to capture the motion of the spine, the back of the seat was partially removed and was replaced by non-stretch tape. To simulate frontal impact, we created acceleration using the sled system. The acceleration pulse was set to create a full sine shape with a maximum acceleration of 8.0 m/s^2 at 500 ms. Kinematic data were captured during the acceleration phase.

4. Data acquisition and analysis

The physical motion of the human body and head-neck-torso kinematics during the low-speed impact were measured using the Raptor-E Series 3D motion capture sys-

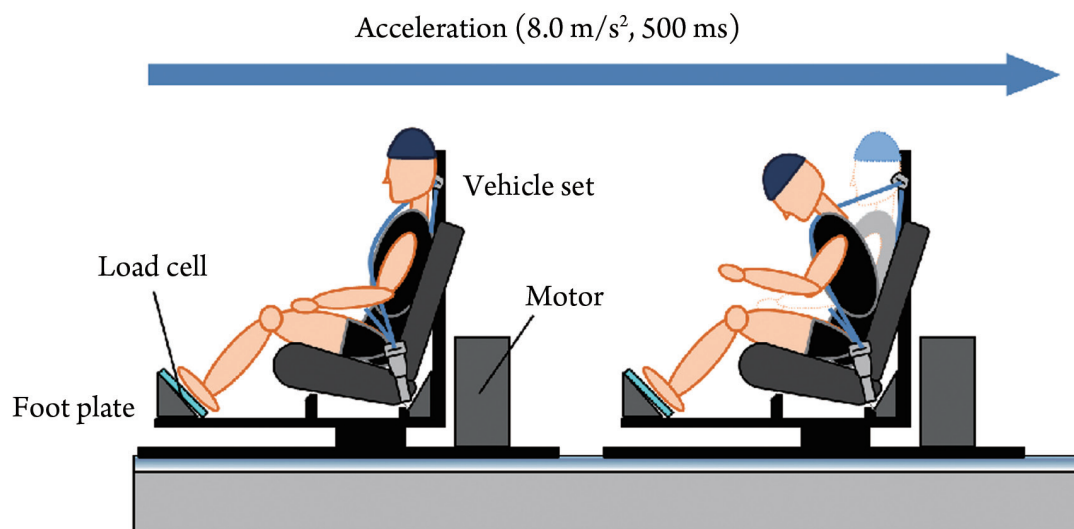


Fig. 1. Low-speed sled system used to evaluate the head-neck-trunk kinematics during frontal impact.

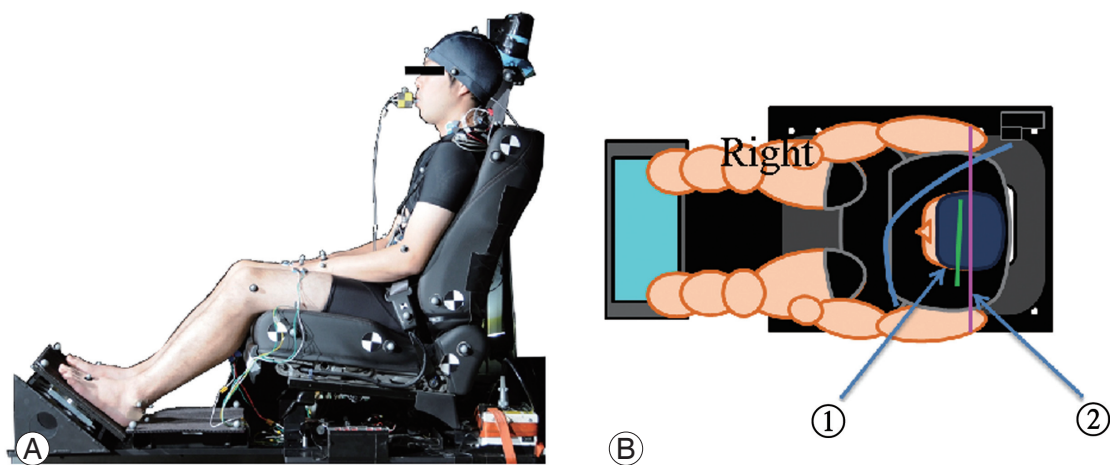


Fig. 2. (A) Seated posture and placement of the reflective markers for the three-dimensional evaluation of kinematics and (B) the lines used to evaluate movement of the head (① right ear to the left ear) and trunk (② right shoulder to the left shoulder) in the axial view.

tem (Nac Image Technology Inc./Motion Analysis Corp., Santa Rosa, CA, USA), which automatically extracts the position of each marker from a video image recorded by eight cameras that are located on the circumference of the testing location and translates those positions into 3D coordinates. The volunteers were photographed from the side and front during the experiments. The resolution of the camera was 1,280×1,024 pixels, and the sampling rate was 500 fps. The images were imported into CORTEX software (Nac Image Technology Inc./Motion Analysis Corp.) and were analyzed. The accuracy of this system is within the error of ± 1 mm and $\pm 1^\circ$. Thus, the angle calcu-

lation system has a considerably high accuracy.

The eight markers that were used for the measurements were placed on the head, right and left ears, first thoracic vertebra (T1), twelfth thoracic vertebra (T12), third lumbar vertebra (L3), and left and right acromia (Fig. 2). The center of the head was defined as the middle point between the right and left ear markers. The kinematics of the head and trunk were evaluated in the sagittal view at the line connecting the center of the head, T1, T12, and L3. In the axial view, the kinematics of the head and trunk were evaluated at the line connecting the center of the head, right acromion, and left acromion. Axial motion of

the head was analyzed at the line connecting the right and left ears, and axial motion of the trunk was analyzed at the line connecting the right and left acromia (Fig. 2).

The rotation angles of the head and trunk were calculated as the changes from the beginning angle during the experiments. A positive angle was defined as a larger angle on the left side than on the right side. The rotation angle of the cervical spine was defined as the difference between the rotation angles of the head and trunk (trunk rotation angle–head rotation angle). The maximum value was defined as the maximum change in the angle of the cervical spine. We compared the maximum change in the rotation angle of the cervical spine in the tensed group with the maximum change in the relaxed group using Welch's *t*-test. The significance level was set at $p \leq 0.05$.

Results

There was a larger movement observed on the photographs in the relaxed state than in the tensed state (Fig. 3). From the front, the observed head movement was more to the side and with more rotation in the relaxed state (Fig. 4).

Regarding the kinematics in the sagittal view, the movement of the T1 marker was greater in the anterosuperior direction in the relaxed state (average maximum longitudinal displacement, 203 mm) compared to the tensed state (average maximum longitudinal displacement, 33

mm), and the movement at the center of the head was greater in the anteroinferior direction in the relaxed state (the average maximum longitudinal displacement, 255 mm) compared to the tensed state (average maximum longitudinal displacement, 56 mm). These data indicated flexing of the cervical spine and extension of the thoracic spine in the sagittal view during the relaxed state.

Regarding the kinematics in the axial view, the average maximum displacement of the right shoulder in the longitudinal direction was 118 mm and 14 mm in the relaxed and tensed states, respectively, and that of the left shoulder was 142 mm and 12 mm, respectively.

The rotation angle of the cervical spine was larger in the relaxed state than in the tensed state (Fig. 5). Only 5 of 6 trials (2 trials for each of the 3 volunteers) were analyzed, because the motion capture was not completed for 1 trial.

The average maximum change in the cervical spine rotation angle was 1.0° in the tensed state and was 8.6° in the relaxed state ($p=0.038$), indicating that the trunk rotated more than the head in the axial view in the relaxed state.

Discussion

By using a sled system and 3D motion capture system to observe the head and trunk movements simultaneously in the sagittal and axial views, we observed a greater change in the head-neck-torso kinematics in the relaxed state

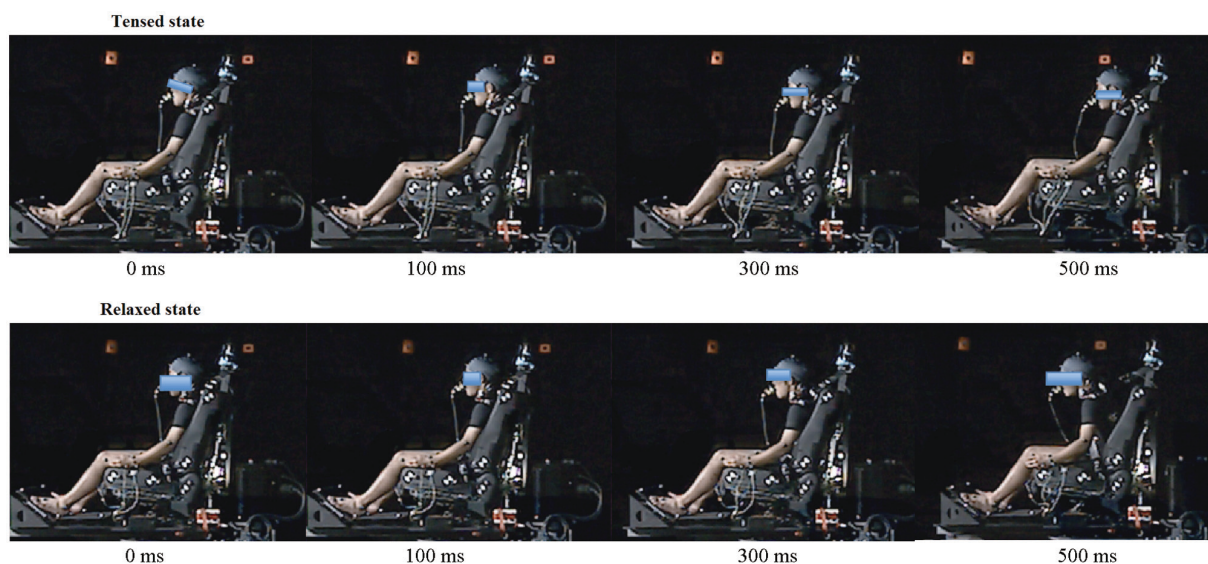


Fig. 3. Images of the low-speed sled system used to evaluate the kinematics during a frontal pre-impact, showing movement in the tensed and relaxed states.

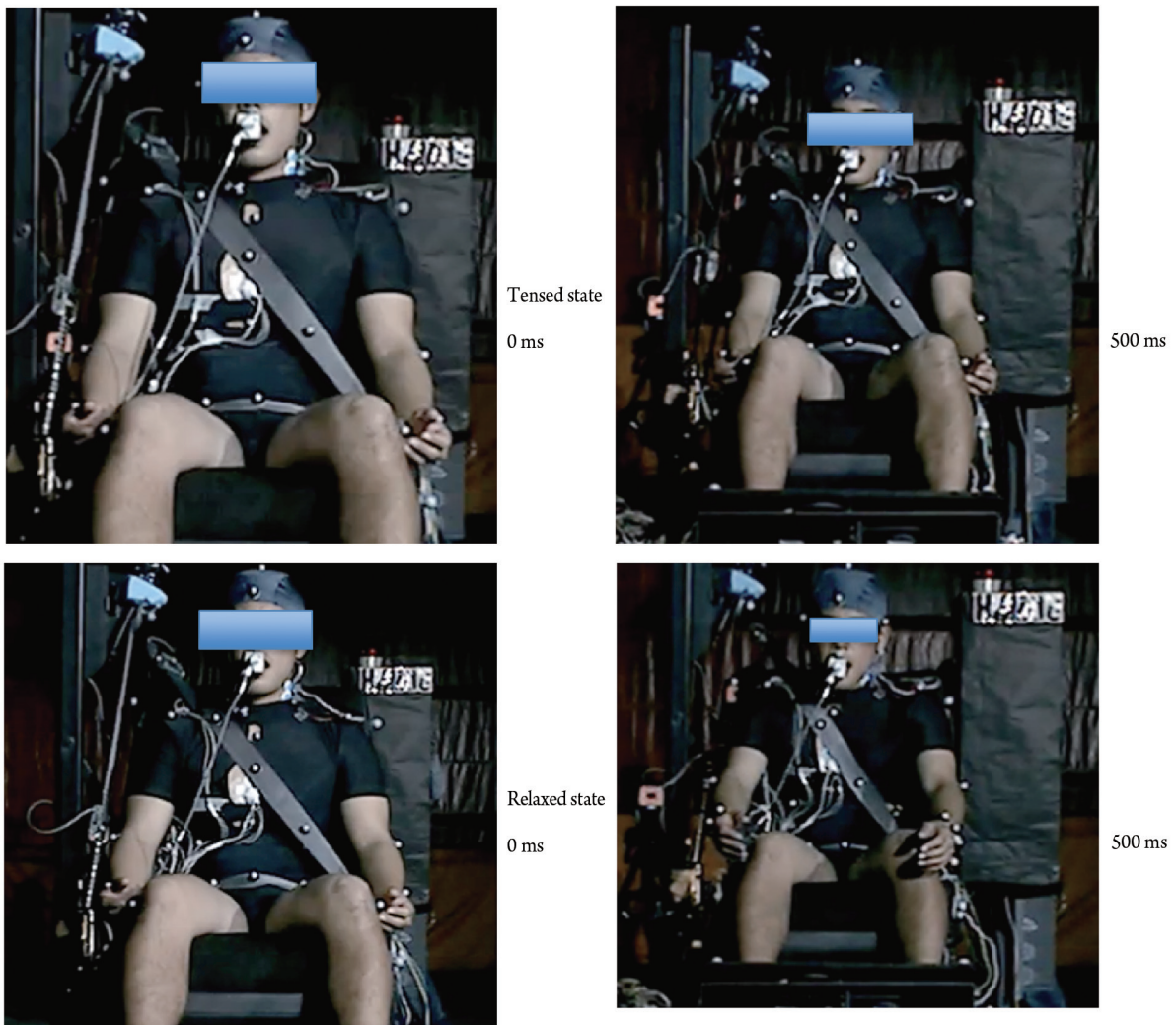


Fig. 4. Images of the low-speed sled system used to evaluate the kinematics during a frontal pre-impact, showing movement in the tensed and relaxed states.

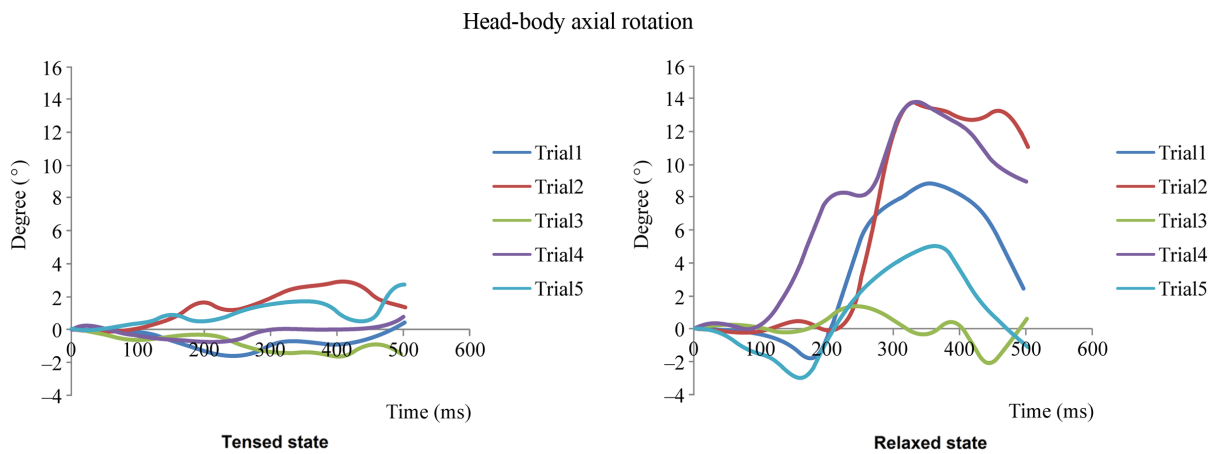


Fig. 5. Axial rotation of the line between the head and trunk in a simulated pre-frontal impact in the relaxed and tensed states.

than in the tensed state in both views. This suggests that the driver may be able to maintain their seated posture if they are able to recognize the impending danger through AEB activation. Then the drivers would be able to brace themselves by tensing their muscles in anticipation of the impact.

It has been reported previously that muscle activity strongly influences the occupant's posture when evaluated in the sagittal view [13-16]. In addition, muscle activity is reportedly an important factor for damage at impact and as a mechanism for injury [26,27].

In the present study, the cervical spine flexed while the thoracic spine extended in the sagittal view during the relaxed state, similar to prior findings [12]. The seat belt secured the volunteer's upper body against a forward movement. The power of the inertial force of the head may have changed to the power of the lower force around the sternum, which was supported by the seat belt. This phenomenon is considered a head-neck flexion-extension motion.

The rotation angle of the cervical spine was larger in the relaxed state than in the tensed state, which may also be explained by a similar mechanism as the flexion of the cervical spine and extension of the thoracic spine. In this case, the trunk rotated as the power of the inertial force of the body changed into the power of the rotation force around the sternum and right shoulder that were supported by the seatbelt. This phenomenon is considered a head-neck rotation motion.

Rotational injuries are important factors in spine injury, and they have been reported in about 18.5% of spine fractures [26]. In fact, rotational motion is an important mechanism for spine injury [4]. An experiment of the finite element method in frontal collision at high energy showed a strong rotational force in the cervical spine [26]. Moreover, rotation of the cervical vertebrae during frontal collision has been reported in human subjects postmortem and in a dummy model [6]. Cervical spine injury from a frontal impact with the air bag has also been reported [28]. Even in our experiment, the trunk rotated more than the head, which translated into rotation of the cervical spine. Since this experiment was conducted at a low speed, the average maximum change in the cervical spine rotation angle was only 8.6° in the relaxed state. However, the impact would be much greater in an actual collision, which would likely result in larger changes in the angle and which would be similar to the human sub-

jects postmortem and in the dummy model. Therefore, it is possible that the cervical spine rotates and flexes toward the air bag during frontal collisions.

A three-point seat belt is an important device for preventing spine injury during frontal collision, and it has become a common feature of automobiles [29]. However, cervical spine fracture caused by the three-point seat belt has been reported [30]. Consequently, a four-point seat belt has been reported as being safer than a three-point seat belt during frontal collision [31]. The four-point seat belt is widely adopted in the automobile industry, because there is a high possibility of crashes, especially with sport utility vehicles. According to previous studies and our present experiment, it is possible to reduce the cervical rotation by using a four-point seat belt, because the four-point seat belt can hold the left shoulder better than the three-point seat belt.

It is important to analyze movements in the sagittal plane (i.e., flexion and extension); however, the combination of movements should be considered in the analysis of the mechanisms of injury to the cervical spine. Therefore, evaluation of movements in the axial view is also recommended in experiments related to impact. In addition, the inclusion of human subjects in these types of experiments is important for evaluating muscle activity, because this is difficult to achieve postmortem or in dummy or computer models.

Some limitations exist in this study. First, since the study subjects participated on a voluntary basis and were young, healthy male volunteers, a selection bias was possible. Another selection bias was the lack of female subjects. Third, this study had a small sample size.

Conclusions

In this simulated experiment on frontal impact, changes in the occupant's posture in the sagittal and axial views were greater in the relaxed state than in the tensed state; therefore, we recommend that motion in the axial view should also be included in impact tests. Moreover, these findings are useful for developing equipment for automobiles to avoid cervical spine injury.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

Acknowledgments

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