# MOTION ANALYSIS OF HUMAN CERVICAL VERTEBRAE DURING LOW SPEED REAR IMPACTS BY THE SIMULATED SLED

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## ABSTRACT

In the pursuit of the mechanism of minor neck injuries, the motion of the cervical vertebrae was analyzed under different conditions such as the seating position and seat performance characteristics. At first, a new impact sled was developed which simulated actual car impact acceleration. This did not involve any risks for the subjects. Ten volunteers participated in the experiment under the supervision of the ethics committee. For test conditions we selected 2, 4, and 6 km/h speeds. Two types of seat performance were used: ordinary car seat and rigid wooden seat. The cineradiography (90 frames/second) recorded the motion of the cervical vertebrae at impact.

It was observed that a downward and rearward extension motion of the C3 compared to the C6 occurred and the cervical spine was compressed in early stage at impact. Moreover, it was found that when the seat was rigid and speeds were increased, the ramping up motion of the body of the subject and the neck compression were more typical. The vertebral motion was qualified and then compared with the differences between crash motion and normal motion. It is concluded here that the compression vertical motion plays an important role in minor neck injuries.

ACCORDING TO A RECENT EXPERIMENTAL STUDY [1] using volunteers, the extension of cervical spine would not exceed the normal physiological motion range, and the hyperextension of cervical spine would not occur as long as the subject was using a head restraint upon rear impact. It is reported, however, that neck injuries caused by rear-end collisions are still occurring with high incidence rates not only in Japan [2] but also in the USA[3] and Europe[4]. It is also reported that the effectiveness of headrest is not statistically clear[5]. One reason why head restraint is not so effective against neck injury is the improper adjustment of head restraint[6]. It is believed that the sitting posture of the subject [7] and the head restraint characteristics [8] are also closely related with the occurrence of minor neck injury. Their correlations, however, have not been clearly determined. It is pointed out that the insufficient clarification of the minor neck injury mechanism is a major bottleneck of the above.

Most of experimental studies on the neck injury mechanism conducted in the past [9-11] were limited to more higher impact speeds or those on frontal collisions, whereas studies on rear end collisions were quite few. It is said that the clarification of correlations among the neck muscular response, motions of cervical vertebrae, intervertebral disc and intervertebral articular injury is necessary, in order to clarify the injury factors including those on severer sequelae of neck injuries. A number of experimental studies using volunteers [12-15] or anthropometric dummies [16-20] have been also carried out, including some reports that analyzed the cervical vertebral motions, but none of them compared such motions with normal physiological motions. In this regard, it was decided to conduct experiments using volunteers for the simulated tests of the actual car rear-end impacts in low speeds, and to compare and analyze the motions of cervical vertebrae upon impact and those in normal condition, in an attempt to clarify the neck injury mechanism according to the characteristic motions of cervical spine during impact.

## METHODS OF EXPERIMENTS

SLED APPARATUS FOR SIMULATION OF CAR REAR-END COLLISION - Cineradiography was used for the analysis of motions of cervical spines of volunteers upon collision. The cineradiographic system was installed at the Tsukuba University Hospital, but there were such restrictions as a limited space for the installation of a simulated sled, limited field vision of the cineradiographic range and the necessity to transfer the system for emergency clinical use. Therefore, a simulated sled with proper specifications to overcome those restrictions was developed and fabricated. The specifications of the

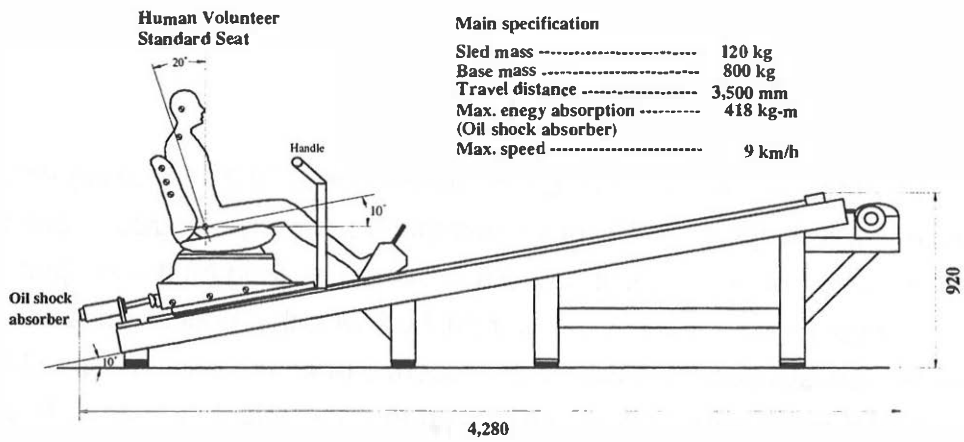



**Figure 1. Sled test apparatus and the main specification**

sled were set to simulate impact accelerations applied to cars which collided with other cars, according to the data obtained by rear-end collision experiments done in the past [2]. The outline and the specifications of the sled system are shown in Figure 1.

CINERADIOGRAPHY - The column of radiation probe of the cineradiographic system (cine-system; Angiorex made by Toshiba Medical Inc.; cine-camera: Arritechno 35, NAC Inc.) can be rotated 180 degrees on a horizontal plane, and the probe itself can be also rotated by $\pm$ 180 degrees. The cineradiographic range is 30 cm x 30 cm, and the probe position can be adjusted vertically in the range of 105 to 130 cm as shown in Figure 2. A position adjuster capable of positioning the volunteer's neck within those ranges on impact was installed on the sled apparatus. The cervical spine motion was recorded by cineradiography at the speed of 90 frames per second and the dose of exposure was 0.073 mG per frame. Approximately 25 frames were recorded for one crash motion.

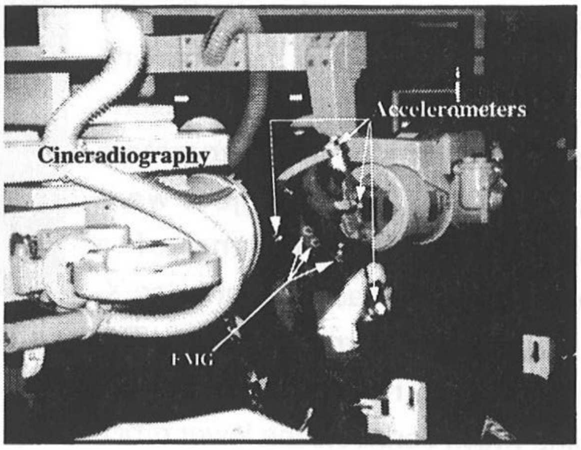


Figure 2 Cineradiographic system and test set-up

VOLUNTEERS AND INFORMED CONSENT - Ten healthy male volunteers without history of cervical spine injury participated in this study. Their average age was 23 years old, and it was confirmed through X-rays that they had no degenerative cervical spine. The study protocol was reviewed and approved by Tsukuba University Ethics Committee, and all volunteers submitted their informed consent in writing according to the Declaration Made in Helsinki [21].

**MEASUREMENTS**

SLED APPARATUS - The sled acceleration was measured with three-axial accelerometers installed on the sled floor, while the sled impact speed was measured with phototubes.

HEAD ACCELERATION MEASUREMENT - Four-channel accelerometers were used for the measurement of head acceleration, since the six-degree of freedom component measuring method [22] was applied. The shear and axial forces and the bending moment acting on the neck upper region (occipital condyle) were measured with this method. The fixture shown in Figures 2 and 3 was fabricated for the installation of accelerometers to the subject's head. A tooth form made of a dental resin molded specifically for each subject was set at the lower portion of the fixture while a magic fastener was attached at the upper portion to fix the subject's head at both the upper and lower portions. Head dimensions and locations of accelerometers installed on each subject were determined by means of a dimensional measurement using X-ray films as shown in Figure 3. The location of anatomic center of gravity of the head was positioned 5 mm in front of the external auditory meatus and 20 mm above the Frankfurt line which connects the lower orbital margin and the center of auditory meatus. This is the similar to the reference point reported by Walker et. al.[23] and Beier et. al. [24].

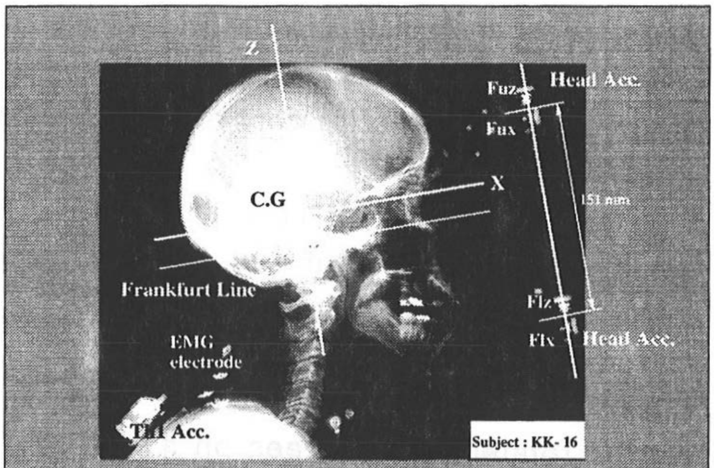


**Figure 3 Lateral view of the skull with marked Frankfurt Line, mounted accelerometers, EMG electrodes and film targets**

THORACIC SPINE ACCELERATION MEASUREMENT - For the analysis of relative motion of the thoracic spine (Th 1: over the spinous process of the first thoracic spine) against the sled, head and the first cervical vertebrae, three-axial accelerometers were attached on the surface of the first thoracic spine as shown in Figure 2. A surgical tape was used to adhere the accelerometers over the thoracic spine skin of the subject, then a double-coated adhesive tape was applied over them.

FRONTAL CHEST ACCELERATION MEASUREMENT - Three-axial accelerometers were installed around the substernal region as shown in Figure 2.

ELECTROMYOGRAPHY - Electromyographic activities were measured by means of electromyogram synchronized with the cineradiography by attaching EMG electrodes onto the skin over bilateral sternoclaidomastoid and bilateral paravertebral muscles as shown in Figures 2 and 3.

CERVICAL VERTEBRAE MOTION ANALYSIS - The cervical vertebral images taken by cine-cameras were digitized and analyzed. Although it is desirable to analyze the cervical vertebral motions overthe entire range of C1 to Th1 in reference to the first thoracic spine, the analysis was done mainly in the range of C2 to C6 due to the limited cineradiographic field of vision. Templates suitable for the shapes of individual cervical vertebrae were produced as shown in Figure 4. This was done to fit them precisely over the individual cervical vertebrae and the spinous process which should move sequentially with time. Based on these, the system of coordinates of the inferior anterior and posterior

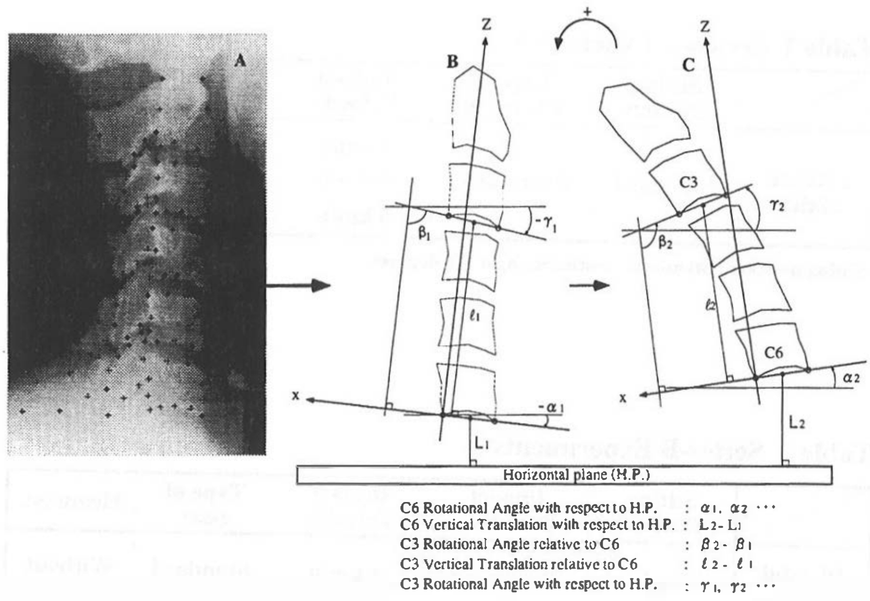



**Figure 4. Template method and measurement items for motion analysis**

points were determined accordingly. From those coordinate values, the angles from the horizontal plane and the vertical translations of individual vertebral segmental bodies were calculated. It was decided to represent the vertical translation by taking the midpoint between the inferior anterior and posterior points of each vertebral body. The motions of entire cervical vertebrae was represented by the changes in the relative rotational angle and translation of the third cervical vertebra from the sixth cervical vertebra due to the limited field of vision. The direction of cervical spine extension was decided as the positive rotational direction, and the upward motion was designated as the positive vertical distance (Figure 4).

There were some cases in which analyzable images could not be obtained from the impact experiments due to the limited cineradiographic field of vision. In such cases, the obtainable images were deemed as the initial values.

## RESULTS

Two series of experiments as described below were conducted. The Series-A Experiments were those using three volunteers in order to find how the differences in impact speed and seatback characteristics affect the cervical vertebral motions where the subjects did not use head restraint as shown in Table 1. The Series-B Experiments used ten subjects (three of them were the same ones used in the Series-A) under the same impact conditions as those of Series-A (impact speed 4 km/h, standard seat) to analyze the diversity of cervical vertebral motions among the subjects as shown in Table 2.

Visual motions of the head-neck-upper torso for each subject could not be observed in experiments using cineradiography. Therefore, the experiments were repeated under

Table 1 Series-A Experimets

| | Sitting Postion | Impact Direction | Impact Velocity | Type of Seat | Headrest |
|---|---|---|---|---|---|
| 3 Adult Males | Standard | Rearward | 2 km/h<br>4 km/h<br>6 km/h | Standard<br>Rigid | Without |

Sitting position : Standard - seatback angle 110 degrees

Table 2 Series-B Experiments

| | Sitting Postion | Impact Direction | Impact Velocity | Type of Seat | Headrest |
|---|---|---|---|---|---|
| 10 Adult Males | Standard | Rearward | 4 km/h | Standard | Without |

Three of subejects were same ones used in the Series-A Experiments

the same impact conditions. The first experiment was conducted to record the cervical vertebral motions by means of cineradiography, while the second experiment was done to record the visual motions by means of high speed video. The cervical vertebral motion was compared between the crash motion and the normal motion. The normal motion means the subject exerts his own force with no motion of the sled. In that case, the volunteer was instructed that the subject's head be kept at a straight position and then moved into maximum forward flexion and/or backward extension.

SUBJECT'S MOTIONS AND RESPONSES OF HEAD AND NECK - The outline of the results is described below regarding the subjects' motions, impact responses and cervical vertebral motions under the impact conditions of 4 km/h speed, standard seat, without head restraint, as the typical case.

They can be divided into 1) the motions observed by high speed video, 2) the acceleration and rotational angle of head, the forces, moment of neck, 3) the cervical vertebral motions observed by cineradiography, and 4) the electromyographic response per unit time after impact. Figure 5A shows the sequential visual motion of the head, neck and upper torso of the subject taken by the high speed video, while Figure 5B shows the sequential images of cervical vertebral motions taken by cineradiography under the same impact conditions. Figure 6 shows the time histories of resultant accelerations of the sled, head, and Th1, and the forces and moment of the neck (around Occipital Condyle).

The reading error with the standard deviation of cervical vertebral images taken by cineradiography was estimated from 10 measurements taken on the same cervical vertebra of each subject. The mean value of deviation was 0.24 mm.

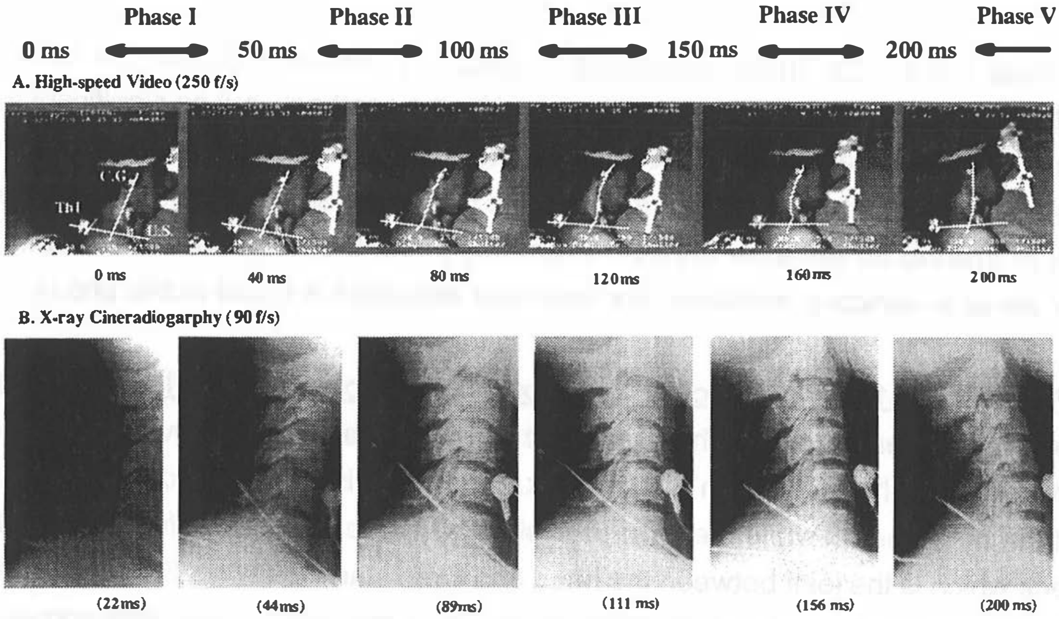



Figure 5 Head-Neck (Cervical Vertebrae) Motion by High-speed Video and X-ray Cineradiography

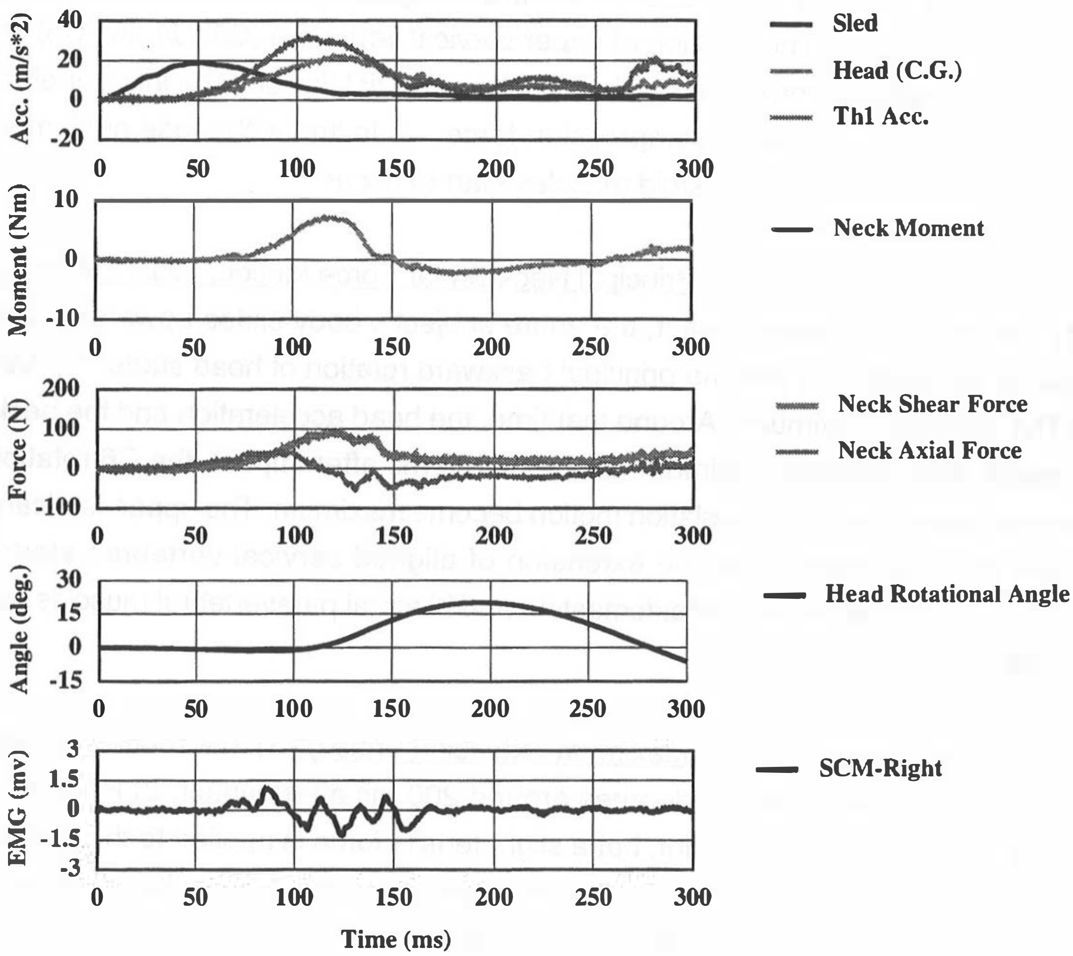



**Figure 6 Time-histories of accelerations of the sled, head, thorax, the impact forces to the neck, and the example of EMG (SCM-right)**

Phase I (0-50 ms, Initial Response Phase) - 1) The subject starts to be pushed against the seatback. The upper torso is pushed by the seatback, but no significant motion of upper torso is observed. 2) About 30 ms after impact, the chest starts accelerating, followed by the acceleration of Th1 about 10 ms later. The sled acceleration reached the maximum around 50 ms after impact. From this point, the head start accelerating. 3) Neither cervical vertebral motion 4) nor muscular response is found in this phase.

Phase II (50-100 ms, Principal Neck Axial Force Motion, Initial Flexion Phase) - 1) The subject's upper torso is pushed against the seatback and starts moving upward at the same time along the inclination of seatback. The head is also moved backward at the same time by its inertia while the torso is pushed by the reaction force from the seatback. The neck which is the joint between the head and torso starts showing S-shape formation, and the head starts showing a slight initial flexion. 2) At this point, a neck axial compression force generated by the slight ramping-up motion of torso and the head inertia is applied to the neck, which reached its maximum at around 80 ms after impact (The compressive axial force on the neck is considered positive in Figure 6). 3) The lower cervical vertebra (C6) starts rotating. The rotation of upper cervical vertebrae (C3, C4 and C5) starts later on, and the cervical vertebrae reach the phase of initial flexion. The intervertebral column is compressed by the axial compression force. 4) In line with these neck motions, the discharge of sternoclaidomastoid muscles start to occur.

Phase III (100-150 ms, Principal Neck Shear Force Motion, Initial Extension Phase) - 1) 110 to 120 ms after impact, the entire subject's body slides upward as it is pushed against the seatback, and the principal backward rotation of head starts. 2) Acceleration of Th1 become maximum. Around that time, the head acceleration and the neck bending moment also become maximum. 3) About 100 ms after impact, the C6 rotational angle and the upward vertical translation motion become maximum. The upper cervical vertebrae follow this C6 motion, and the extension of aligned cervical vertebrae starts. 4) The discharge of bilateral stemoclaidomastoid and bilateral paravertebral muscles by the neck stretch reaction continue.

Phase IV (150-200 ms, Maximum Extension Phase) - 1) The rotational angle of head becomes approximately 20 degrees around 200 ms after impact. 2) Head acceleration hardly occurs around this point, but a slight tensile force is applied to the neck due to the seatback rebounding. 3) Individual cervical vertebrae rotate while keeping practically the same extension alignment. 4) The electromyographic activities of the neck disappear around 200 ms.

Phase V (200 ms, Final Phase) - 1) The torso starts going down from the upward motion due to the seatback rebound force. 2) The seatback rebound acceleration appears at Th1. 3) The cervical vertebrae show the maximum extension, then start to resume the original positions. 4) Electromyographic activities are not found in this phase.

Motions and impact responses of subjects under the impact conditions of 4 km/h, standard seat, without head restraint have been described. Characteristic phenomena of the experiments with a rigid wooden seat are a greater torso ramping-up motion and a smaller rebound than the experiments with the standard seat.

SUBJECTIVE SYMPTOMS OF SUBJECTS AFTER IMPACTS - A clinical doctor had personal interviews with the subjects at the time of MRI, date of experiment, one day, 2 weeks, one month and 12 months after experiment, and handed out questionnaires to the subjects. Presence/absence of any subjective symptoms and details of such symptoms in daily life, if any, were recorded accordingly, but no symptoms were diagnosed among the ten subjects.

## DISCUSSION

HEAD/NECK LOADING AND CERVICAL VERTEBRAL MOTIONS - McKeever[25] proposed a hypothesis in 1960 that the compression force was important as a whiplash injury factor according to his mathematical simulation model analysis. However, the hypothesis was not verified by experiments until recently. The author conducted similar experiments on volunteers in 1993[2], and found that the axial compression force applied to the cervical spine was a vital factor. McConnell[15] conducted a car rear-end collision experiment and also found that this axial compression force influenced the occurrence of neck injury. In this study, therefore, it was decided to investigate the relationship between those cervical vertebral motions and the axial compression force applied to the cervical

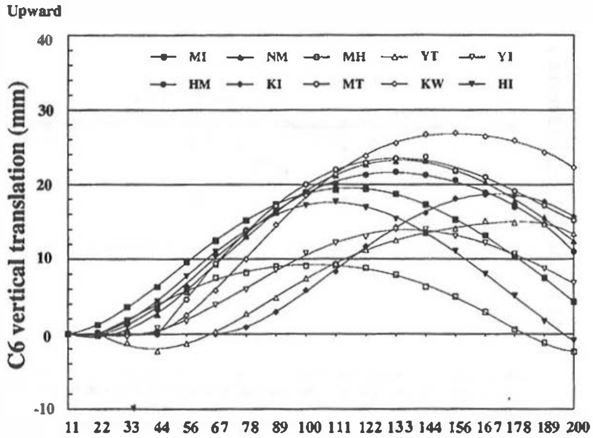



Figure 7 C6 motion - vertical translation

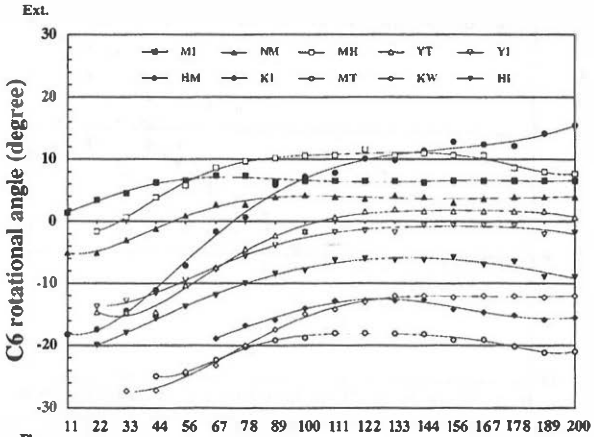



Figure 8 C6 motion - rotational angle

spine, using ten volunteers under the impact conditions of 4 km/h, standard seat, without head restraints.

The segmental motion of C6 upon impact in terms of rotational angle as shown in Figure 7 and vertical translation as shown in Figure 8 reveals that the rotational angle of C6 increases over time and reaches its peak at around 100 ms after impact but it hardly changes there after. The vertical translation of C6, on the other hand, reaches its peak approximately 100 to 150 ms after impact while rotating backward, and goes up by around 30 mm (Figure 7). This motion occur similar to the change in the cervical spine axial force around C1 as shown in Figure 6. When looking at the translation as a relative displacement of C3 against C6 as shown in Figure 9, it is found that C3 is displaced downward relative to C6. This indicates that the cervical spine is compressed by impact, and this compression motion is presumably generated by the axial force applied to the cervical spine.

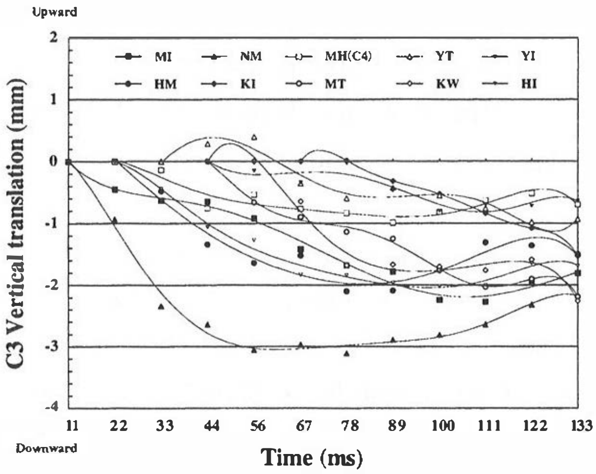



**Figure 9 C3 motion relative to C6 - vertical translation**

INFLUENCES OF SITTING POSTURE (ALIGNMENT OF CERVICAL SPINE) AND TORSO RAMPING-UP MOTION - The initial angle of C3 against the horizontal plane of C6 - i.e., the initial angle of subject's neck is inclined backward and shows a positive inclination angle (extension position) of C6 in one subject (MI) only. All of the remaining 9 cases show negative inclination angle (flexion position), indicating that their necks were slightly inclined forward. The diversified rotational angles of C3 can be divided roughly into the three groups - a group showing cervical spine extension immediately after impact

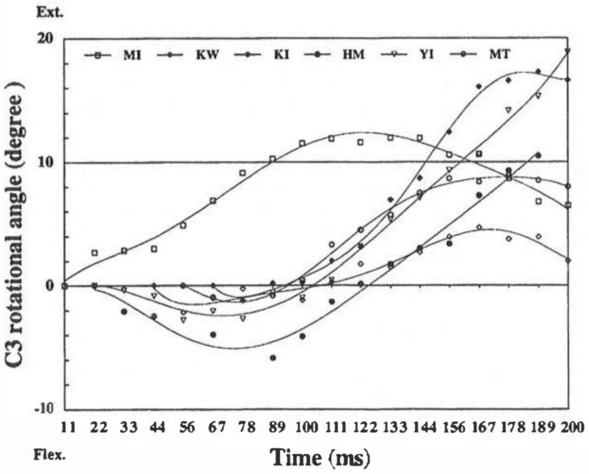



**Figure 10 C3 motion relative to C6 - rotaional angle (extension and flexion-extension groups)**

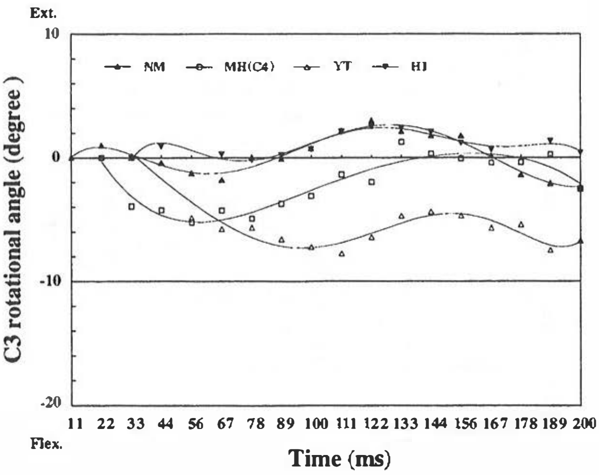



**Figure 11 C3 motion relative to C6 - rotaional angle (steady group)**

as shown in Figure 10, a group showing cervical spine extension after flexion motion until around 100 ms after impact (Figure 10), and a group without showing any clear extension as shown in Figure 11. It can be explained for the first group that the reason for showing the extension of cervical spine immediately after impact was that the angle of C3 against the horizontal plane of C6 was inclined backward, different from the remaining nine cases.

As discussed so far, the inclination of cervical spine (subject's sitting posture) influences the extent of flexion and extension of cervical spine after impact. Moreover, the extent of flexion and extension are influenced not only by the relative positions of head and neck against the head restraint, but also influenced markedly by the torso ramping-up condition. In other words, it is indicated by the above that the occurrence of neck injury should not be discussed simply by the relative positions of head and neck against the head restraint.

CERVICAL VERTEBRAL MOTIONS BEYOND NORMAL PHYSIOLOGICAL MOTION RANGE - A typical example (YI) of motions of the C3, C4, C5 and C6 cervical vertebrae is shown in Figure 12. The pattern of rotational angle of each vertebra of this subject upon normal extension of cervical spine by the subject's own action is shown in Figure 13. It is observed that the rotational angle between C4 and C5 is greater than others in normal extension, showing that C4 and C5 have greater mobility than others. C6 shows a larger rotational angle than other cervical vertebrae until 100 ms or so after impact, which reaches the peak around 100 ms after impact. The rotational angle is smaller for other cervical vertebrae up to this point, but the upper vertebra becomes greater, thereafter, compared with the slight rotational angle for C6. The rotational angle pattern on impact compared with normal motion is as follows.

The cervical motion on impact is reversed by the pattern in normal motion about 100 ms after the initial stage of impact. The motion of the lower vertebrae becomes greater than the upper vertebrae. This means that the torso motion causes the cervical spine to

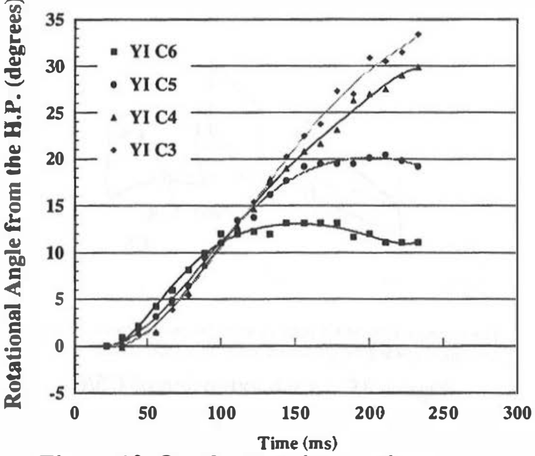



**Figure 12 Crash extension motion - Pattern of rotational angle of each vertebra (from the horizontal plane)**

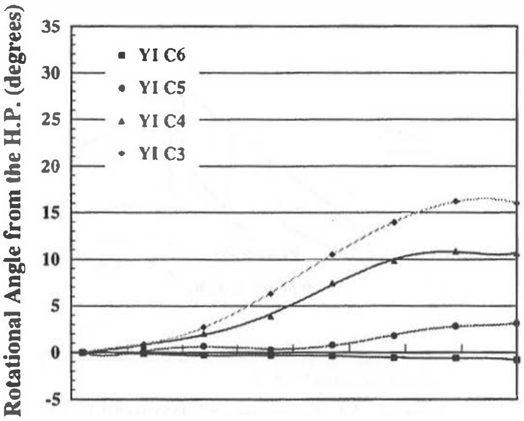
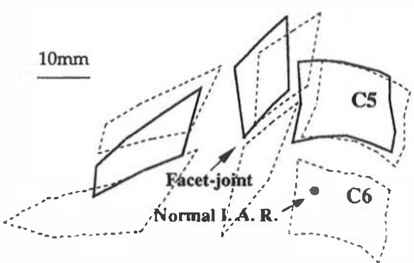



**Figure 13 Normal extension motion - Pattern of rotational angle of each vertebra (from the horizontal plane)**

move up from the lowest vertebra to the upper vertebrae. In the normal extension motion, cervical movement proceeds gradually from upper vertebrae as shown in Figure 13. This opposite directional motion is not physiological in nature in relation to the cervical spine and is likely to have relation to the clarification of injury mechanism. The rotational angle is highest at C5/C6, and the force should be significantly different from that in normal motion, as the compression force on the cervical spine is also added to the force.

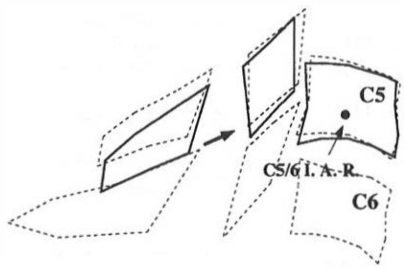
ROTATION CENTER AND ABNORMAL MOTIONS OF VERTEBRAL BODIES - The rotation center of each vertebral body was analyzed for the clarification of typical motions of vertebral segments having large localized rotational changes. It was also found that the segmental motion between C5 and C6 shows greater rotational angle compared to the upper segments as shown in Figure 12. This upward travel of rotation center was observed in cases where the vertebral segment flexed until 100 ms after impact, then extended thereafter. The vertebral segment motions involving the upward travel of Instantaneous Axis of Rotation (I.A.R.) were found in the lower cervical facet joints such as one case of C4/C5, one case of C5/C6 and two cases in C6/C7. This is mainly because facet joins in the lower cervical bodies are easier to move as the orientation angles in the lower facet joints against the horizontal plane become rather more inclined than those of the upper facet joints where a compression force is applied.

The comparison of such segmental motions with those in normal condition shows that the C5 inferior articular facet surface rotate smoothly around the normal I.A.R. while keeping proper clearances with the superior articular facet surface in normal condition as shown in Figure 14. The posterior edges of C5 inferior articular facet moves toward the C6 facet surface in the crash motion as shown in Figure 15. The upward travel of I.A.R. suggests the interferences among vertebral articular facets such as the posterior edge of C5 inferior articular facet and the C6 facet surface. The upward travel of rotation center is




The C5 inferior articular facet surface rotates smoothly around the normal I. A. R.

**Figure 14 Normal extension of C5/6.**




The posterior edge of C5 inferior articular facet shows downward movement toward the C6 superior articular facet surface.

**Figure 15 Crash extension of C5/6.**

not observed in normal motion, which is presumably related closely with the mechanism of vertebral articular injuries.

## CONCLUSIONS

A new low speed impact sled apparatus was developed, and experiments were conducted on ten volunteers by means of cineradiography for the analysis of cervical vertebral motions. The experimental data were compared with those in normal condition, and following points were clarified regarding the characteristic motions during impact. Their relationships with neck injury have been discussed and summarized below.

1) Upon rear-end collision, the torso ramping-up motion and the axial compression force due to the head inertia are applied to the cervical spine simultaneously. A flexion motion occurs in the early phase of 50 to 100 ms after impact then extension occurs. The cervical spine compress slightly in this phase due to the axial compression force.
2) The ramping-up motion of torso, combined with the state of cervical vertebral alignment, influences the flexion and extension of cervical spine markedly. Therefore, it is necessary to consider not only the relative positions of the head, neck and head restraint, but also the torso push-up force applied to the cervical spine and the state of cervical vertebral alignment as evaluation parameters for neck injury in rear-end collisions.
3) The motions of cervical vertebrae are beyond the normal physiological motions. The rotational angle of cervical vertebrae during impact is particularly high between the fifth and sixth vertebral facets, which is quite different from that in normal condition.
4) The lower vertebral center of rotation moves upward on impact which makes articular facets collide each other easily. Such abnormal segmental motion cannot be found in normal condition, which we believe is related with the injury mechanism of intervertebral articular facets.

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