Influence of Seat Properties on Human Cervical Vertebral Motion and Head/Neck/Torso Kinematics During Rear-end Impacts

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ABSTRACT

The properties of seat with head restraint are important parameters for the optimum design of the seat system performance during rear-end impacts. The aim of the current study is to verify the influence of different seat properties on human cervical vertebral motion using X-ray cineradiography and head-neck-torso kinematics under low speed rear-end impacts.

Six volunteers participated in the experiment under the supervision of an ethics committee. The subject sat on a seat mounted on a sled that simulated actual car impact acceleration. Impact speeds (4, 6, and 8 km/h), and seat stiffness (hard or soft) without headrest were selected as the influence parameters for the cervical vertebrae at impact. The cervical vertebrae motion was recorded by 90 f/s X-ray cineradiography. It is also analyzed to quantify the cervical motion and the head-neck-torso motion under different impact conditions with the combination of influence parameters.

From the current study, it is said that the difference in seat characteristics affects the timing of the straightening of the spine, which in turn markedly affects the load to be applied to each cervical vertebral segment. In case of higher stiffness of seat, the motion of upper torso in the initial phase of impact becomes sharp, and the axial compression force on the cervical spine tends to become greater. Even if the stiffness is low, however, the rebound of the upper torso is greater in the latter half of impact.

Therefore, it is necessary to verify more clearly the straightening of the spine and cervical vertebral motion with respect to the difference in seat characteristics in order to design a seat system that can reduce minor cervical injury.

THE MECHANISM OF THE SO-CALLED "WHIPLASH INJURY" (distortion of cervical spine; traumatic neck syndrome) has not been clearly understood, and the causality between the objective physical/medical observations and the subjective symptoms is said to be unclear[1,2]. In this regard, the gap between the subjective symptoms and the objective observations has been a major problem of whiplash. It can be said that this uncertainty, combined with issues involved in automobile injury insurance, has resulted in the negligence in conducting sufficient studies required for the clarification of those minor neck injuries.

The incidence rates of neck injuries remain high [3,4,5], despite the belief that the hyperextension of cervical spine would not occur as long as the occupant is using a headrest. There is a strong presumption that some injury mechanism other than the improper use of headrest must be involved as a cause of neck injuries. It is also pointed out that headrests including the current seat systems do not have adequate functions and structures for the suppression of neck injuries.

The occupant is subject to various kinds of forces upon rear-end impact, which tend to differ among individual occupants due to differences in seating position and seat cushion stiffness, which are presumably related with the incidence of neck injuries[6,7,8,9]. It is also pointed out that the clarification of correlations among the neck muscular responses, motions of cervical vertebrae and intervertebral disc and intervertebral articular injuries is necessary for further pursuit of injury factors including those of impairments, as well as those of relatively minor neck injuries.

The authors et. al. reported earlier that a force causing ramping-up of the subject's torso was observed upon rear-end impact, and an axial force due to the head inertia was applied to the cervical vertebrae, which facilitated the flexion and extension of the cervical spine, according to the experiments conducted using cineradiography with the participation of volunteers[10,11]. It was also reported that such cervical vertebral motions were beyond the normal physiological range, which were closely related with the facet joint injury mechanism - a mechanism that must have caused neck injuries[12]. Those non-physiological motions tended to occur as a result of seat characteristics - with a rigid seat in particular - but clear tendencies could not be determined at that time.

It was decided, therefore, to use both a standard seat of mass production (hereafter called "S-seat") and a rigid seat made of wood (hereafter called "R-seat") to investigate the effect of seat characteristics on the head-neck-torso motions, change of the spine configuration (straightening) and cervical vertebral motions through experiments with the participation of volunteers.

METHODS OF EXPERIMENTS

VOLUNTEERS AND INFORMED CONSENT - Six healthy 23 year old male volunteers participated in the series of experiments. It was confirmed through X-ray photographs that they did not have any degenerative cervical spine. The protocol of experiments was reviewed and approved by the Tsukuba University Ethics Committee, and all volunteers submitted their informed consent in writing according to the Helsinki Declaration[13].

SLED APPARATUS - The apparatus is capable of sliding the sled freely on a 4-meter long rail angled at 10 degrees, and colliding the sled against a damper with the maximum speed of 9 km/h. The sled impact performance is designed according to the actual car rear-end impact experiments conducted in the past. Namely, an oil shock damper was installed to simulate accelerations applied to the struck car and to ensure proper control. One of the two kinds of seats - i.e., the S-seat or the R-seat - was mounted on the sled in each test. The schematic diagram of the sled apparatus is shown in Figure 1.

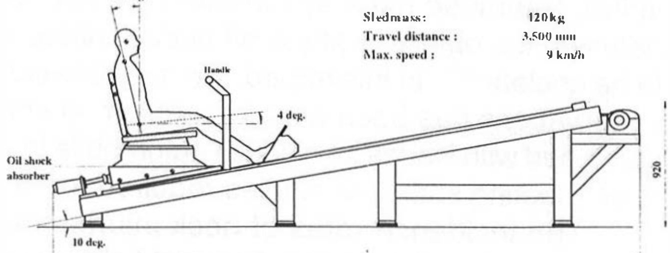


Figure 1. Outline of Sled test apparatus

CINERADIOGRAPHY - The column of radiation probe of the cineradiographic system (cine-system:

Angiorex, Toshiba Medical Inc.; cine-camera: Arritechno 35, NAC Inc,) can be rotated 180 degrees on a horizontal plane around a pillar supporting the system, and the probe itself can be rotated ± 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 (Figure 2). Cervical vertebral motions were recorded by cineradiography with the speed of 90 frames per second. The dose of exposure was set at 0.073 mG, and approximately 25 frames were recorded for each crash motion.

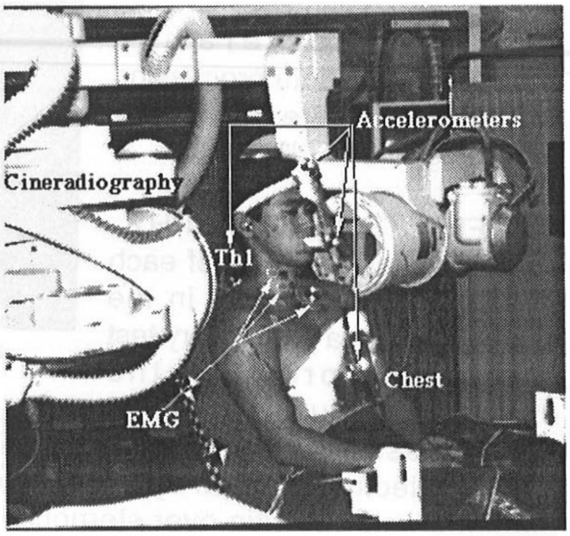


Figure 2. Cineradiography system and test set-up

SLED ACCELERATION AND SPEED - Tri-axial accelerometer (KYOWA ELECTRONIC INSTRUMENTS CO. LTD.) was installed on the sled floor along the inclination of the rail. The sled speed immediately before impact was measured by means of phototube.

HEAD ACCELERATION AND NECK LOAD - As the head motion was two-dimensional in the X-Y plane, four-channel accelerometers with the combination of two sets of biaxial accelerometers for X and Y axes were used in the measurement [4)]. The shear and axial forces and the bending moment acting against the upper region of neck (occipital condyle) were measured with this method. The fixture shown in Figure 3 was fabricated for the installation of accelerometers on the head of each subject. A teeth form made of a dental resin molded particularly for each subject was set at the lower portion of the fixture, while a fastening tape was attached at the upper portion to fix the accelerometers on the subject's head.

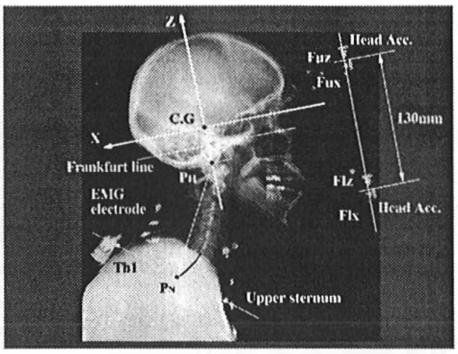
LOCATION OF HEAD C.G. - The location of anatomic center of gravity of the head was assumed by the determination methods reported by Walker et al.[14)] and Beier et al. [15)]. The position of the head C.G. was located 5 mm in front of the external auditory meatus and 20 mm above the Frankfurt line which connects the lower orbital margin and the center of auditory meatus. See Figure 3.

TH1 ACCELERATION - The acceleration of the first thoracic vertebra was measured by attaching tri-axial accelerometer over the surface of the first thoracic vertebra with a surgical tape over which a double coated tape was adhered.

CHEST ACCELERATION - Tri-axial accelerometer was installed on the front chest around the sternum region. The accelerometer was adhered onto an aluminum plate attached to the front chest with rubber bands.

PELVIS ACCELERATION - The acceleration was measured by attaching tri-axial accelerometer onto the surface of the first sacrum with a surgical tape over which a double coated tape was adhered.

The acceleration measurements, data processing and analysis were conducted according to SAE J211.



Fux: Frontal upper x-axis accelerometer
Fuz: Frontal upper z-axis accelerometer
Flx: Frontal lower x-axis accelerometer
Flz: Frontal Lower z-axis acceleometer
C.G.: Center of Gravity
PH: Intersection point on head-neck joint
PN: Intersection point on neck-torso joint
U.S.: Upper sternum point

Figure 3 Coordinate system and lateral view of the head/neck/torso with mounted accelerometers, EMG electrodes, VTR targets and the marked points for X-ray picture

ELECTROMYOGRAPHY - The muscular condition of each subject was measured in the relaxed state in a preliminary test conducted prior to the experiment. Muscle activities were measured by means of surface electromyogram synchronized with cineradiography. EMG electrodes were attached onto the skin over sternoclaidomastoid muscles, paravertebral muscles and trapezius muscles on the subject's left side, and sternoclaidomastoid muscles on the right side. The electrodes with diameter of 5 mm were arranged as bi-polar electrodes with a distance of roughly 2 cm between electrode centers. The EMG signal was sampled at 5000 Hz and then recorded on OVDAS (On Vehicle Data Acquisition System) data acquisition system.

VISUAL MOTION ANALYSIS ON HEAD/NECK/TORSO KINEMATICS -In order to analyze the motions of the subject upon impact, target marks were adhered over two accelerometers on the upper and lower portions of the head, accelerometers on the Th1 and front chest, and over the skin around 5 mm below the auditory meatus close to the center of gravity of the subject's head, shoulders, above the 12th rib, iliac crest and the upper sternum (Figure 4). For the analysis of relative motions of the head, neck and torso, small lead balls of about 3 mm in diameter were inserted between the subject's skin and target marks near the auditory meatus, Th1 and the upper sternum. They were used as the reference points for the determination of the head-neck joint and the head-torso joint in X-ray photographs as shown in Figure 3. Target marks were also placed at the upper and lower portions of the seatback sides, and photographs were taken with high-speed video cameras (MEMORECAMERA Inc.) at the speed of 500 frames per second. The photographed images were incorporated in ImageExpress (NAC Inc.) and analyzed.

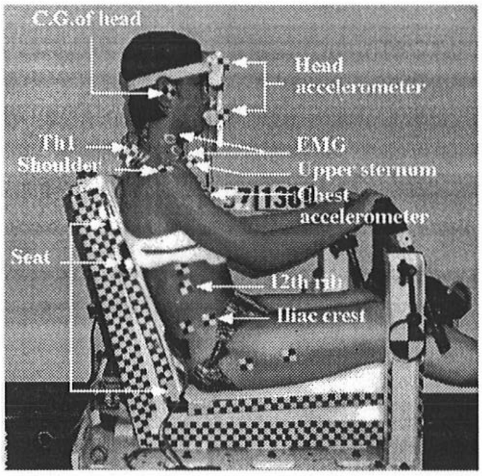


Figure 4. Lateral view of the head/neck/torso with mounted accelerometers, EMG electrodes, tragets for high-speed video

DEFINITIONS OF HEAD-NECK JOINT, NECK-TORSO JOINT, HEAD-NECK LINK & ROTATION ANGLES OF HEAD, NECK AND TORSO - The head-neck joint, neck-torso joint, head-neck link, and rotation angles of head, neck and torso are defined as follows and shown in Figure 3.

Head-neck joint (PH)	: the intersection point of the extended line from the posterior tangent of cervical vertebra C2 and the skull base tangent parallel to the Frankfurt line on the head as found in simple X-ray photograph
Neck-torso joint (PN)	: the intersection point of the line connecting individual small lead balls attached to the surfaces of Th1 and the upper sternum, and the extended line from the curve formed by the posterior of cervical vertebra
Head-neck link (HNL)	: the line connecting the head-neck joint and the neck-torso joint
Head angle (HA)	: the inclination of the line passing through the head's center of gravity (CG) and parallel to the Frankfurt line
Neck angle (NA)	: the inclination of the line connecting the head-neck joint and the neck-torso joint
Upper torso angle (UTA)	: the inclination of the line connecting the Th1 and the upper sternum

DEFINITION OF SPINE EXTENSION - The human spine becomes straight upon rear-end impact due to the impact against the seat back, at which time the neck-torso joint moves upward. The spine extension caused by this straightening was quantified. The linear distance between the neck-torso joint and each target on the iliac surface as shown in Figure 4 is defined here as the spine extension.

CERVICAL VERTEBRAL IMAGE ANALYSIS AND LOCATION OF INSTANTANEOUS AXIS ROTATION - Images of individual cervical vertebrae photographed with a cine-camera were digitalized and analyzed. Templates suitable for the shapes of individual cervical vertebrae were produced first, using an image analysis software (CANAVAS 3.5.3 developed by Denebe Systems Inc.) (Figure 5). This was done to fit them precisely over the images of individual cervical vertebrae which would move sequentially with time, for the determination of the system of coordinates of the anterior and posterior points of inferior cervical vertebrae. The angles and vertical displacements of individual vertebral segments were calculated from the values shown on the system of coordinates.

The system of coordinates was set such that the inferior posterior point of each vertebral segment was the original point, the line passing through the inferior anterior was the X-axis, and vertical line against the X-axis passing through the original point was the Y-axis. The distance between the anterior point and exterior point of each inferior vertebral segment was defined as 1 in order to minimize the comparison error, and the motions of individual vertebral segments were compared. Furthermore, the intersection point of vertical bisectors of the line connecting the two points of inferior anterior vertebral segment before and after the displacement, and the line connecting the two points of inferior exterior vertebral segment before and after the displacement was determined and quantified as the instantaneous axis rotation (IAR) of each vertebral segment.

The backward rotation (extension) of each vertebral segment was defined as the positive direction of rotation, and the upward displacement was defined as the positive vertical distance (Figure 5). There were some cases where analyzable images starting from the moment of impact could not be obtained due to the limited photographic range of the cineradiography. In such cases, the values of obtainable images were deemed as the initial values.

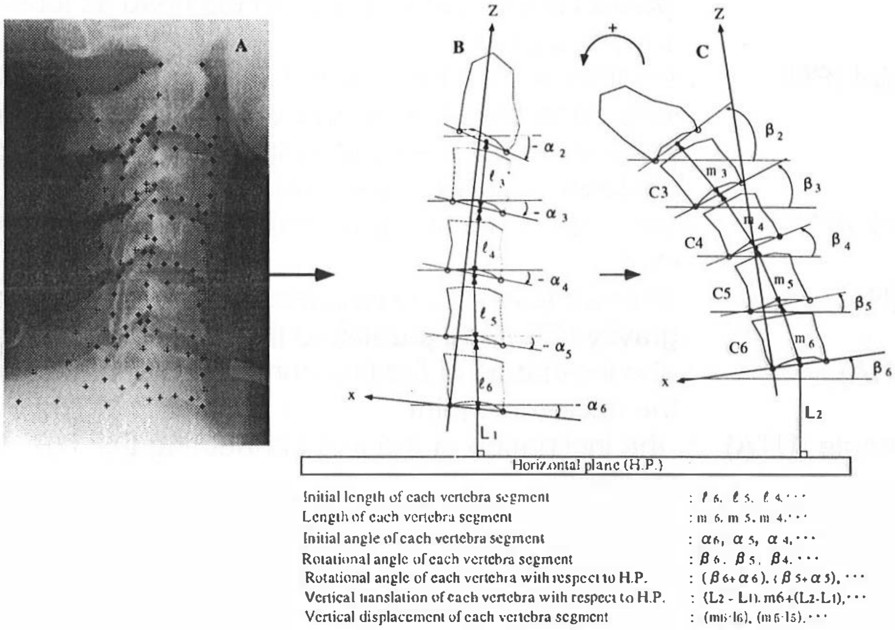


Figure 5. Template method and measurement items for vertebral motion analysis

RESULTS

SUBJECTS' MOTIONS AND RESPONSES OF HEAD, NECK AND TORSO - Series of experiments were conducted on six volunteers without using any headrest in each case as shown in Table 1, in order to investigate the effect of seatback stiffness (using R-seat and S-seat) on the subjects' motions.

In case of experiments conducted with cineradiography, visual motions of the subjects (head, neck and torso) could not be recorded. Therefore, the first experiment was conducted with cineradiography to record cervical vertebral motions, then another experiment was conducted under the same impact conditions but using high speed video cameras to record the VTR visual motions.

In this paper, results of experiments conducted at the impact speed of 8 km/h using the R-seat without headrest will be described. The following will be summarized per phase of impact as sequential changes with time: 1) head/neck/torso motions observed with high speed video camera, 2) acceleration at each region of subject and the loads against the neck, 3) cervical vertebral motions observed by cineradiography, and 4) the electromyographic responses.

Figure 6 a) shows sequential visual motions of the head, neck, and torso of the

Table 1 Test Matrix

	Impact velocity	Sitting position	Type of seat	Headrest
6 adult male	4 6 km/h 8	Standard	Rigid Standard	Without

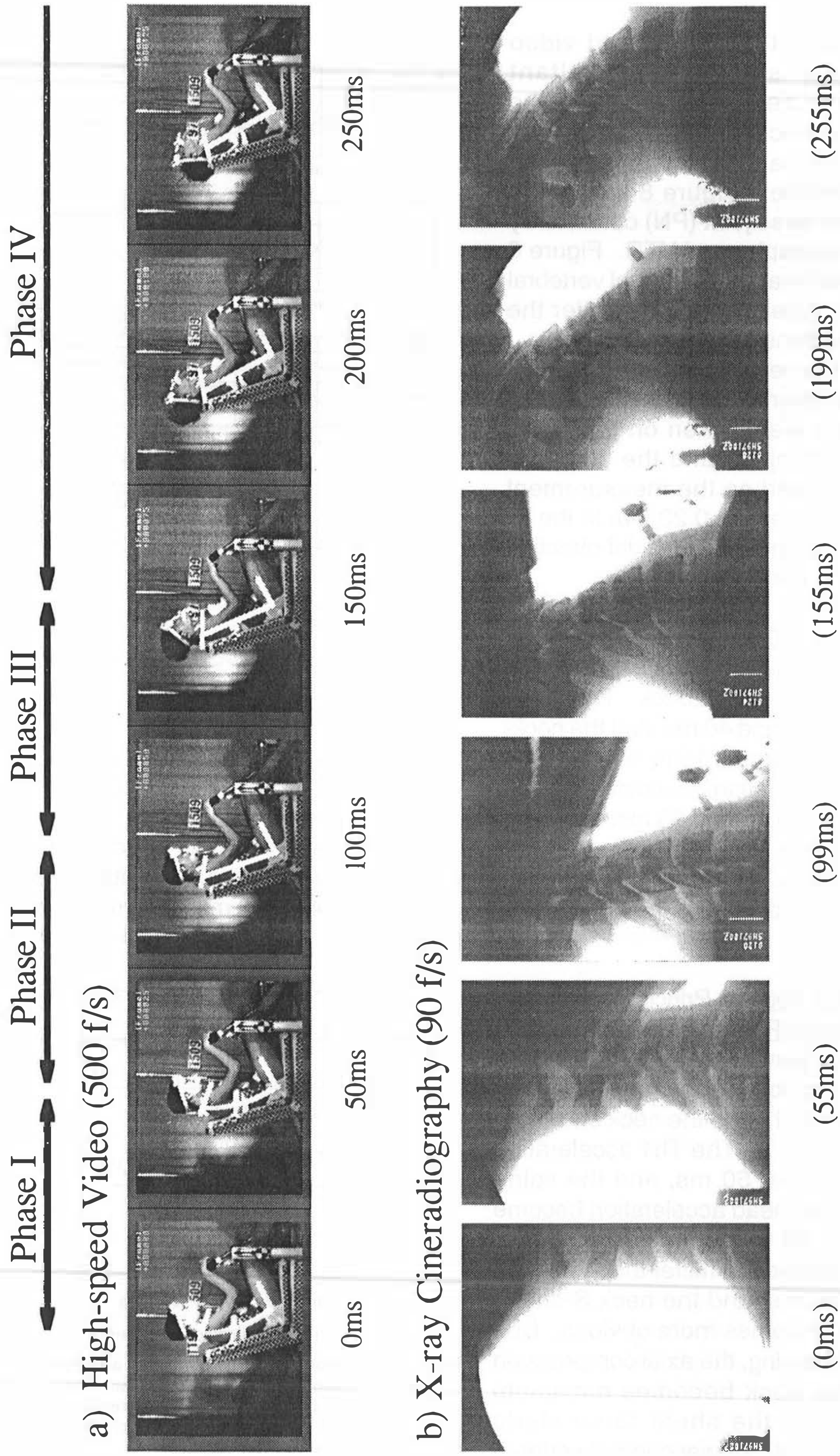


Figure 6. Head-neck-torso motion by high-speed video and cervical vertebrae motion by X-ray cineradiography

subjects taken with the high speed video camera. Figure 7 shows the resultant accelerations of sled, head, Th1, and pelvis, the force acting on the neck (around C1), rotation angles of head, neck and torso, together with the EMG time histories. Figure 8 shows the trajectories of neck-torso joint (PN) obtained by simple X-ray photographs and VTR. Figure 6 b) shows sequential images of cervical vertebral motions taken by cineradiography under the same impact conditions.

Regarding the reading error in cervical vertebral images taken with cineradiography, 10 measurements were taken on the same vertebra of each subject, and the standard deviation was deemed as the measurement error. The mean value was 0.23 mm in the X-axial direction, 0.24 mm in the Y-axial direction and 0.48 degree in the rotation angle.

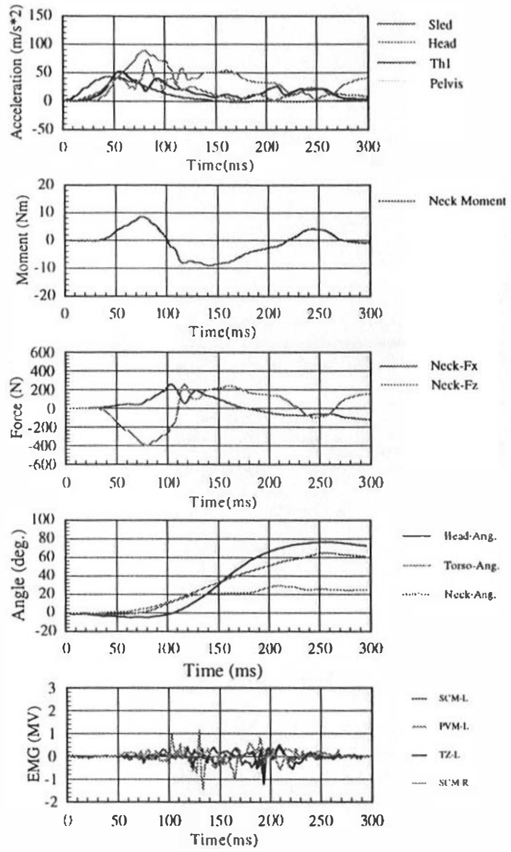


Figure 7 Time-histories of accelerations of the sled, head, thorax, forces on neck, angles of head, neck, torso and the EMG responses on the subject for the R-Seat (8km/h)

Phase I (0 to 50 ms, Initial Response Phase) - 1) The subject's back starts to be pushed back against the seatback. The spine starts straightening around 40 ms, and the neck-torso joint goes up. 2) About 15ms after impact, the pelvis starts accelerating, and both Th1 and head start accelerating around 35 ms. The sled acceleration becomes maximum around 45 ms. 3) No significant motion of head or neck is found in this phase. However, the extension of spine is observed, and a slight neck bending moment is also found in the direction of forward flexion. 4) Neck muscular response is not found.

Phase II (50 to 100 ms, Principal Neck Axial Force Motion, Flexion Phase) - 1) With the spine straightening more significantly, the head moves backward in parallel to the torso due to inertia. The torso tends to arch, and the neck shows an S-shape deformation. 2) The Th1 acceleration becomes maximum at 60 ms, and the spine straightening and the head acceleration become maximum around 80 ms. The rotation of the neck becomes greater and faster than the head rotation around 80 ms, and the neck S-shape deformation also becomes more obvious. Due to the spine straightening, the axial compression force against the neck becomes maximum around 80 ms, and the shear force starts increasing gradually. 3) A lower cervical vertebra

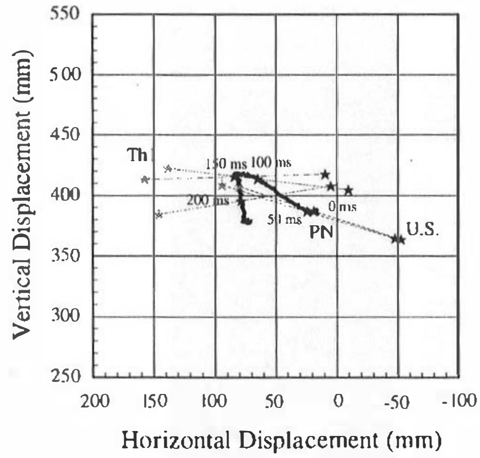


Figure 8 **Motion of neck-torso joint and the change in torso angles shown by the connecting lines between the Th1 and the U.S. for each 50ms interval after impact**

(C6) shows a slight initial flexion, then starts an extension. The extension of upper vertebrae starts later on. 4) In accordance with these neck motions, EMG discharges start from paravertebral and trapezius muscles around 60 ms.

Phase III (100 to 150 ms, Principal Neck Shear Force Motion, Flexion-Extension Phase) - 1) The torso is pushed against the seatback, and the arched rotation of the upper torso becomes maximum around 130 ms, which initiates the principal head extension. 2) Around 130 ms, the neck-torso joint starts going down. The head rotation angle starts becoming larger than that of neck, with the neck shear force becoming maximum around 110 ms. 3) Around 130 ms, the extension angle of the sixth cervical vertebra becomes maximum, and the upward displacement also becomes maximum. 4) In accordance with the neck extension, EMG discharges from sternoclaidomastoid, paravertebral, and trapezius muscles continue around 70 ms.

Phase IV (150 ms, Final Response Phase: Maximum Extension Motion) - 1) The rotational extension angles of the head and neck become maximum around 250 ms, then they start resuming the original positions thereafter. 2) Around 150 ms, the torso ramping-up becomes roughly maximum, while the head acceleration starts to drop gradually. The Th1 acceleration, head bending moment, shear force and axial compression force also start to drop gradually. 3) The upper vertebrae maintain nearly the same extensional alignment, and keep on rotating in line with the 6th vertebra. 4) Muscular discharge from the neck almost completely disappears around 250 ms.

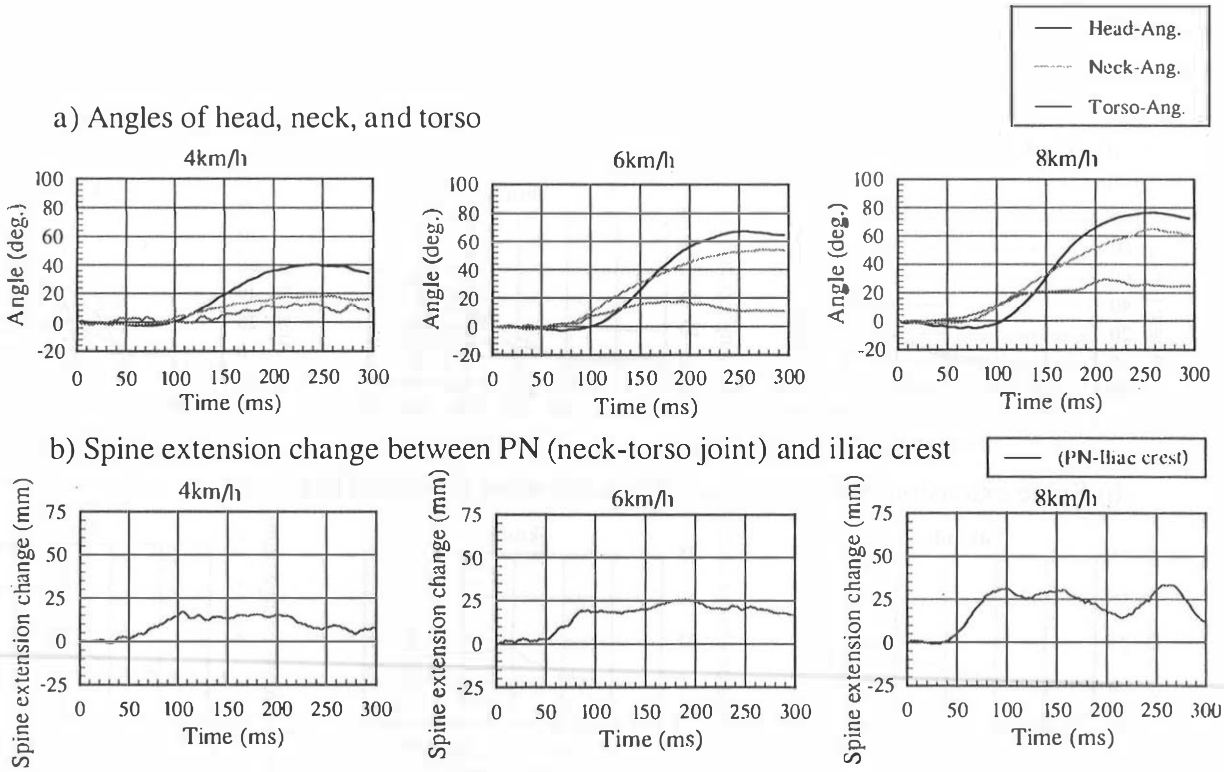


Figure 9 Angles of head, neck, and torso, spine extension change for the different impact speeds of 4, 6, and 8 km/h (R-seat)

MUSCULAR TENSION - It was found that the pre-impact tension of muscles affected the head-neck motions at a low rear-end impact speed [10, 11]. It was also found, however, that the effect of electromyographic responses hardly existed where the muscles were relaxed. The EMG monitored under this study shows that the subjects were relaxed, and the neck muscular response could not have affected the head-neck motions.

EFFECT OF SEAT STIFFNESS - Figures 9 and 10 show the comparison of the angles of head, neck and torso, and the extension of spine of the same subject measured at the impact speeds of 4, 6 and 8 km/h, respectively, for the S-seat and the R-seat. Figure 11 shows the time histories of resultant accelerations of the sled, head, Th1, and pelvis and the moment and forces acting on the neck at the impact speed of 8 km/h with the S-seat.

DIFFERENCES IN HEAD, NECK AND TORSO MOTIONS - The rotation angles of head, neck and torso, and the spine extension are greater with the R-seat than with the S-seat as the impact speed becomes higher (Figures 9 and 10). Both the timing when the head, neck and torso rotations started, and the timing when the spine extension started are earlier for the R-seat. That is, the rotation start timing is in the range of 100 to 150 ms and the extension start timing is in the range of 80 to 90 ms with the S-seat, while the former is in the range of 60 to 120 ms and the latter is in the range of 40 to 50 ms with the R-seat which are much earlier than those of the S-seat. This is because the torso sinks into the seatback for the S-seat while the spine becomes straight together with the deflection of seatback itself, whereas the arched spine collides against the rigid seatback, then the

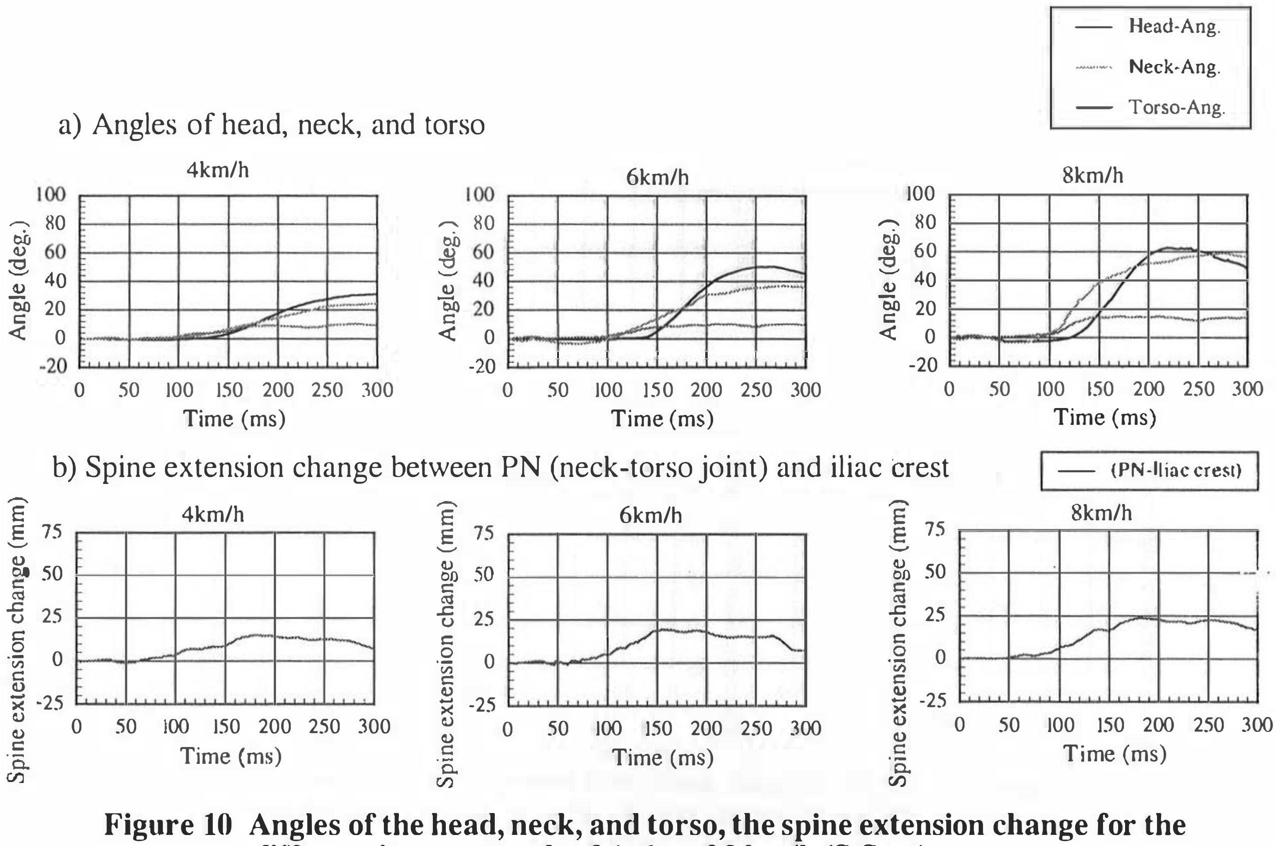


Figure 10 Angles of the head, neck, and torso, the spine extension change for the different impact speeds of 4, 6, anf 8 km/h (S-Seat)

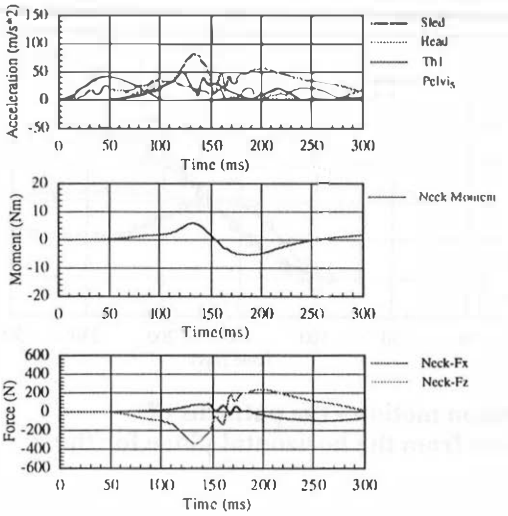


Figure 11 Time-histories of accelerations of sled, head, thorax, and the forces on the neck of the same subject of the Rigid seat at the S-seat (8km/h)

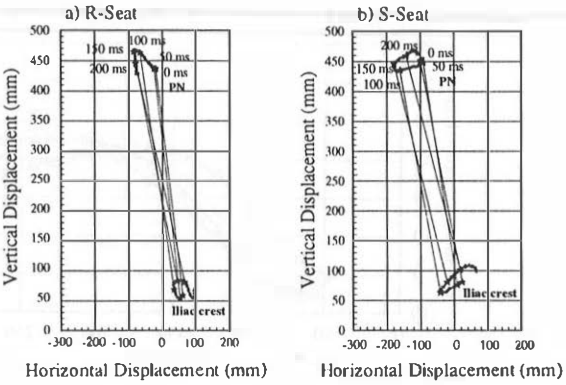


Figure 12 Trajectories of the neck-torso joint and iliac crest, and comparison of the pattern of spine extension changes between the R and S seats on the same subjects at 8 km/h

spine is extended and straightened for the R-seat.

Such phenomena are clearly found in the comparison of spine extension between the S-seat and the R-seat shown in Figure 12. In case of the S-seat, the straightening of spine becomes maximum around 150 ms, while the entire torso is sinking into the seat, then the entire torso is lifted due to the rebound of the torso. In case of the R-seat, on the other hand, the torso ramps up along the rigid seatback around 40 ms immediately after impact, then the straightening of spine becomes maximum around 100 ms, then the torso drops around 150 ms.

DIFFERENCES IN TH1 ACCELERATION AND NECK LOADS - The Th1 acceleration starts around 50 ms after impact with the S-seat, and it reaches the maximum value of 50 m/s^2 around 130 ms (Figure 11). With the R-seat, on the other hand, the Th1 acceleration starts around 20 ms, and the maximum value of 55 m/s^2 is reached around 60 ms (Figure 7). In other words, the Th1 acceleration rise timing is earlier and the maximum acceleration is greater for the R-seat than for the S-seat. The neck bending moment rise timing is around 40 ms for the R-seat, while it is around 50 ms for the S-seat, with the maximum 8 Nm for the R-seat around 75 ms, and 6 Nm for the S-seat around 120 ms. The neck shear force rise timing is around 50 ms for the R-seat, and around 100 ms for the S-seat, with the maximum value of 240 N for the R-seat around 110 ms, and 40 N for the S-seat around 140 ms. The axial compression force rise timing is around 35 ms for the R-seat, and around 50 ms for the S-seat, with the maximum 400 N for the R-seat around 80 ms, and 300 Nm for the S-seat around 120 ms.

As described in the foregoing, the stiffer the seat, the earlier is the rise timing for the Th1 acceleration, and for the loads (bending moment, shear force and axial compression force) against the neck. Their absolute values also become greater as the seat becomes stiffer. The neck axial compression force in particular becomes markedly greater.

EFFECT OF SEAT PROPERTY ON CERVICAL VERTEBRAL MOTIONS - For clear determinations of cervical vertebral motions of the same subject at the impact speed of 8 km/h between the cases for the R-seat and for the S-seat, time histories of motions of

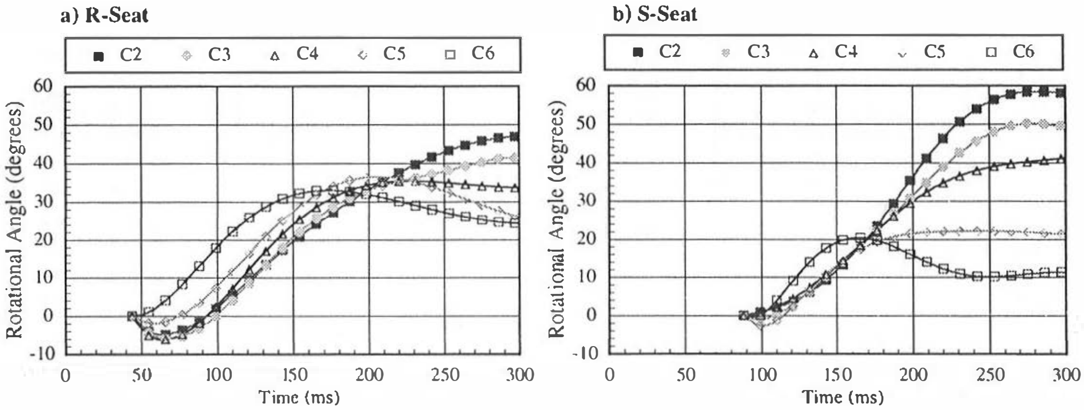
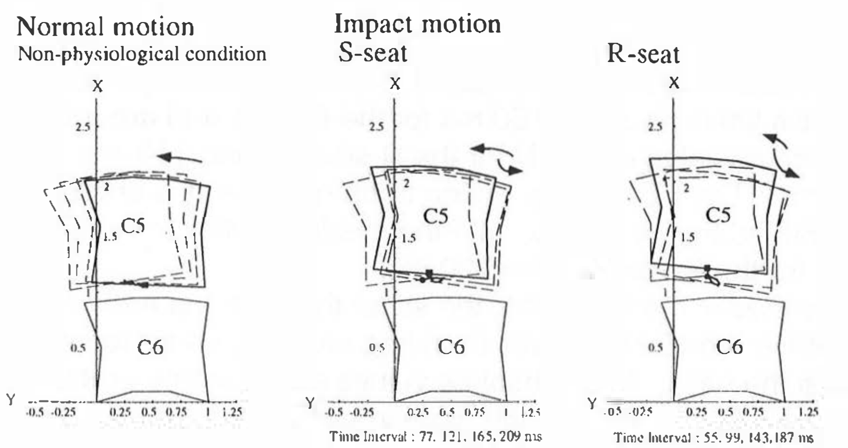


Figure 13 Comparison of the crash extension motion - the patterns of rotational angle of each vertebra from the horizontal plane for the R and S seats at 8 km/h impact

individual cervical vertebrae and their rotation angles were measured. Figure 13 shows the comparison of the rotation angles between the two types of seats (see reference 11) and 12) for the rotation angles in normal physiological motion). For the comparison of cervical vertebral motions among the normal condition in the physiological state and the impact conditions in the two types of seats, the motions of C5 relative to C6 having a great difference among each cervical vertebra are shown in Figure 14.

The motions of cervical vertebra C5 relative to C6 in normal physiological state are characterized by the smooth circular lateral slide toward the Y-axis while making backward rotation (extension) without making forward rotation (flexion). With the S-seat, C5 shows flexion in line with a slight downward motion toward the X-axis relative to C6 in the initial phase of impact, then slides laterally after the downward motion has become maximum (maximum compression) while making an upward motion and a backward rotation. With the R-seat, on the other hand, C5 shows similar flexion but the downward motion and the backward rotation in extension are greater and the lateral slide is smaller than for the S-seat. According to the variation in rotation angle and the motions in vertical (X-axial) and



The solid lines show the initial position of C5.
The dotted lines show the C5 motion for each 44ms interval after the initial obtainable image.

Figure 14 Comparison of cervical vertebral motions among the normal condition in the physiological state and the impact conditions in the two types of seats

lateral (Y-axial) directions , it is found that the motions of C5 relative to C6 for the R-seat are smaller in terms of radius of curvature and the rotation in lateral direction, compared with those for the S-seat. It is suggested that the instantaneous axis rotation of C5 relative to C6 tends to shift upward and the impingement between the lower and upper cervical vertebrae tends to be damped more easily with the R-seat than with the S-seat.

SUBJECTIVE SYMPTOMS ON SUBJECTS AFTER IMPACTS - A clinical doctor had personal interviews with the subjects at the time of MRI prior to the experiment, on the day of experiment, one day, one week and one month after the experiment, and handed out questionnaires to the subjects.

Presence/absence of any subjective symptoms and the details of such symptoms in daily life, if any, were recorded accordingly. Although one subject out of six recognized neck discomfort a day after the experiment, the discomfort disappeared within a few days. No other symptom was recognized thereafter.

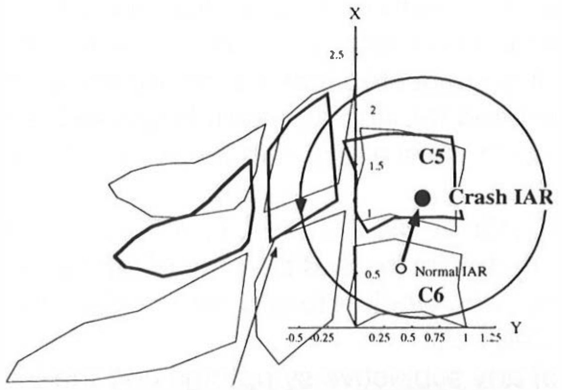
DISCUSSION

EFFECT OF SEAT STIFFNESS AND HEAD- NECK-TORSO KINEMATICS - The stiffness of seat is an important factor for the optimum design of occupant restraint system aiming at the enhancement of new performance, such as to combine the occupant restraint system and the seat belt system into one system, to develop a smart restraint system, etc. In this regard, studies are being made on a proper seat system with headrest. Parkin et al. [16)] pointed out that the incidence of minor neck injuries would tend to increase if the seat stiffness was increased. Svennson et al. [17)] also pointed out that the elastic rebound caused by the seatback would facilitate the incidence of whiplash injury. Lundell et al. [18)] proposed 1) to reduce accelerations against the occupant, 2) to minimize the relative motions between the neck and torso and 3) to suppress the forward travel of occupant by means of seat belt as the biomechanical guideline for the reduction of neck injuries. However, only fragments of studies have been conducted so far for the clarification of such a mechanism. According to the analysis of torso and cervical vertebral motions conducted in this study, on the other hand, the causality between the seat stiffness and the incidence of cervical vertebral injuries in impact phase may be pointed out as follows.

The difference in seat stiffness affects the motion of torso upon impact, which in turn markedly affects the loads against each cervical vertebral segment. If the stiffness is increased, the torso-neck joint upward motion in the initial phase of impact in particular caused by the straightening of spine tends to become sharper, and the axial compression force against the cervical spine tends to become greater as a result of the above. If the seat stiffness is reduced, on the other hand, the head-neck link will be displaced if the rebound is great particularly in the latter phase of impact, which presumably causes an intense shear force against the upper cervical spine. Hence the development and design of a proper seat system with headrest in accordance with this mechanism will be necessary.

SEAT STIFFNESS AND CERVICAL VERTEBRAL MOTIONS - As has been analyzed in the foregoing regarding the cervical vertebral motions, the compression force acts on the cervical spine upon impact, and the cervical vertebral motions are affected by their alignment [11)].

According to a recent analysis [19, 20, 21)] on the location of instantaneous axis rotation in normal physiological motions of cervical vertebrae, the IARs in the normal physiological



Posterior edge of the C5 inferior articular facet shows downward movement toward the C6 facet surface.

Figure 15 C5 upward IARs position against C6 for the R-seat (8 km/h)

motion are located in C6 vertebral body. On the other hand, IARs in the non-physiological motion travelled upward and are found in C5 vertebral body. Examining this motion with an upward shifted IAR, the posterior edge of the C5 inferior articular facet demonstrates downward movement toward the C6 facet surface and appears likely to collide with it. This facet motion is completely different from normal physiological motion [20]. This is presumably the mechanism that causes the collision between the vertebral joints - namely, a facet joint injury.

Figure 15 shows the C5 upward IARs position against C6, according to the motions of C5 and C6 with the R-seat as shown in Figure 14. When the seat stiffness is increased, the spine straightening becomes more obvious, and the compression force against the cervical spine and the upward travel of the position of IAR increase, facilitating the occurrence of non-physiological vertebral motions. It is deduced that such phenomena constitute conditions that facilitate the impingement of facet joints we are proposing.

It is strongly suggested by the foregoing findings that the development of a proper dummy is imperative, one which allows simulations of impact responses of cervical spine including more flexible human cervical vertebral motions. With existing dummies [22, 23], it will be difficult to simulate such human spine motions and evaluate seat systems more properly.

CONCLUSIONS

For further clarification of the effect of seat stiffness on human cervical spine motions, the effect on the human head/neck/torso kinematics has been studied by means of X-ray cineradiography using volunteers. Moreover, quantitative determinations of human spine extension, location of IAR, and the cervical spine motions were conducted, together with the creation of patterns. Consequently, the following findings were obtained.

1) Rotation angles of the head, neck and torso and the extension of cervical spine are earlier for both the Th1 acceleration and the loads against the neck, and their absolute values are also greater for the R-seat than for the S-seat. The axial compression force also becomes particularly large for the R-seat.
2) As the seat stiffness increases, the rise timing becomes earlier for both the Th1 acceleration and the loads against the neck, and their absolute values also become greater.

3) With the R-seat, the deflection of seat itself is absent, and the extension of cervical spine caused by the straightening of spine alone and the ramping-up motion of torso occur. With the S-seat, the straightening of spine occurs together with the deflection of seatback itself. The torso sinks into the seatback, then ramps up.
4) The spine straightening tends to intensify as the seat stiffness increases. It is vital to control the spine straightening and the sinking of the torso into the seatback when designing a seat system.
5) For the R-seat, the motion of C5 relative to C6 in the downward direction is greater but the lateral slide is smaller than for the S-seat. The location of the C5 IAR tends to go up easier for the R-seat.
6) The phenomena mentioned above suggest that the axial compression force against the cervical spine is increased and the vertebral IAR goes up, making the facet joint contact easier.
7) The development of a proper dummy capable of simulating cervical vertebral motions is imperative, as existing dummies are incapable of evaluating non-physiological motions of the cervical vertebrae.

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