Head/Neck/Torso Behavior and Cervical Vertebral Motion of Human Volunteers During Low Speed Rear Impact: Mini-sled Tests with Mass Production Car Seat

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ABSTRACT

The purpose of this study is to clarify the neck injury mechanism during low speed rear impact. Low speed rear impact tests on human volunteers were conducted using a mini-sled apparatus with a mass production car seat. Head/neck/torso behavior and cervical vertebral motion were analyzed and strains on the cervical facet joint were determined. The effect of differences on gender, seat back angle, sled acceleration and muscle condition to the head/neck/torso behavior and the cervical vertebral motion were also discussed. Moreover, the risk of neck injury in a mass production car seat environment was evaluated by comparing the strain values to the results from a previously reported test that used a rigid seat environment.

Keywords: Neck, Sled Tests, Volunteers, Mass Production Car Seat, Cervical Vertebral Motion

NECK INJURIES have a higher incidence during rear impact collisions compared to other collision patterns (Ono et al., 1996; Eis et al., 2005). Therefore, clarification of the neck injury mechanism during rear impact calls for urgent attention.

Studies simulating rear impact using human volunteers have been conducted to analyze the occupant's behavior during rear impact collisions (van den Kroonenberg et al., 1998; Brault et al., 1998; Siegmund et al., 2000; Tencer et al., 2001; Hernandez et al., 2005; Dehner et al., 2007). However, in almost all of the studies, human kinematics were only considered and subsequently used for predicting the occurrence of neck injuries. In a previously reported study, low speed rear impact tests on human volunteers using a mini-sled apparatus with a rigid seat and without a head restraint (Ono et al., 2006) were conducted. The cervical vertebral motion of the human volunteer was recorded using a cineradiography system and the strains on intervertebral disc and facet joint were also calculated. However, in a real car condition, a mass production car seat is used instead of a rigid seat. The structure of the mass production car seat, the shape of the head restraint, and the mechanical properties of the seat have a significant effect on the head/neck/torso behavior and the cervical vertebral motion during low speed rear impact.

Welcher et al. (2001) conducted tests on human volunteers and determined the effects of seats with different properties on the human subject's kinematics. Kleinberger et al. (2003) conducted tests using dummies and evaluated the influence of the seat back and the head restraint properties on the occupant's dynamics using an existing neck injury criterion. However, there has been almost no reported research on the effect of a mass production car seat on cervical vertebra motion during rear impact.

Mertz et al., (1971) reported that the tension on the neck muscles reduced the head flexion during rear impacts. Authors also reported that the head flexion was decreased by 30% to 40% in the tension condition (Ono et al., 1999). Moreover, from the tests with a rigid seat, it was found that the cervical vertebral motion could not be restrained during the tension condition, although the head behavior was restrained significantly (Ono et al., 2006). However, this observation requires to be clarified in mass production seat environments.

In this study, low speed rear impact tests on human volunteers in a mass production seat environments were conducted to determine the influence of the differences in gender, the seat back angle, the sled acceleration and the muscle condition to head/neck/torso behavior and the cervical

vertebral motion. The results were used to evaluate the risk possibility of neck injuries during rear impacts in mass production car seat environments.

EXPERIMENTAL METHODS

MINI-SLED APPARATUS

A mini-sled apparatus was designed by considering the maximum acceleration and duration of impact, based on the previous low speed rear impact testing (Ono et al., 1999) to ensure the volunteers' safety. Fig.1 shows a schematic view of the mini-sled apparatus. A carriage was set on horizontal rails and a mass production car seat was mounted on the carriage. The seat has a Whiplash Injury Lessening (WIL) technology (Sawada et al., 2005) developed by Toyota Motor Corporation, that allowed the occupant's torso to sink into the seatback during rear impact, controlling the relative motion between the head and torso. The rear impact was simulated by utilizing a force, from a motor placed on the anterior part of the apparatus, to pull the carriage frontward. A damper was used on anterior part of the rails to decelerate the carriage.

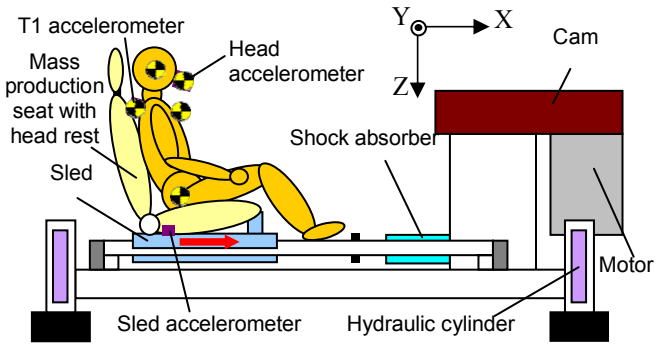

Fig.1 Schematic view of the mini-sled apparatus

PHOTOGRAPHY OF THE HEAD/NECK/TORSO BEHAVIOR USING A HIGH SPEED VIDEO CAMERA

In order to obtain the head/neck/torso behavior of the volunteers during the rear impact, a high speed video camera (Redlake MotionXtra HG-100K) with a photographic capability of 500fps was used. Markers that were attached to the volunteers' bodies were able to be tracked and analyzed.

PHOTOGRAPHY OF THE CERVICAL VERTEBRAL MOTION USING A CINERADIOGRAPHY SYSTEM

In order to obtain the cervical vertebral motion, a cineradiography system (Philips BH-5000) from the University of Tsukuba Hospital, with a photographic capability of 60fps was used. Using this system, 1024 x 1280 pixels of sequential images was obtained. Based on the sequential images, the cervical vertebrae were digitized and then analyzed.

MEASUREMENT METHOD

The sled acceleration was measured by mounting an accelerometer on the carriage. In order to calculate forces acting on the head/neck/torso during the rear impact, a 3-axis accelerometer and a 3-axis angular velocimeter were placed in the volunteer's mouth and on the body surface above the T1 spinous process, this enabled measurement of translational acceleration and angular velocity of head and T1. Furthermore, strain gauges were attached to the head restraint pole to determine the reaction force of the head restraint. The relationship between the strain measured and reaction force generated was determined through a calibration test. In order to obtain the muscle activities of the volunteers, electrodes were attached to the body surface above the representative muscles including the neck muscles. Electromyography (EMG) of the muscles was measured during the tests. In addition, the contact condition between volunteer's body and the seat was measured by attaching touch sensors to the surfaces of the occipital region of the head, back, head restraint and seat back. This sensor was

capable of monitoring the start time and finish time of the contact between the volunteer's body and the seat.

TEST CONDITION

The sled accelerations used for the experiments were 28m/s^2 (females only), 33m/s^2 (both) and 40m/s^2 (males only). Fig.2 shows the time history of the sled accelerations and velocities. The seat back angle was set to 20° and 25°. Subjects were asked to perform the tests in both relaxed and tensed muscle states. The average and standard deviation of the backsets measured during the initial condition are shown in Fig.3.

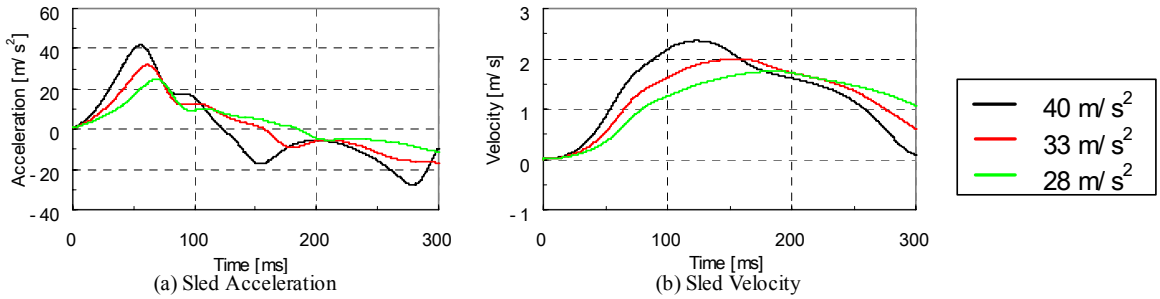

Fig.2 Time history of the sled accelerations and velocities

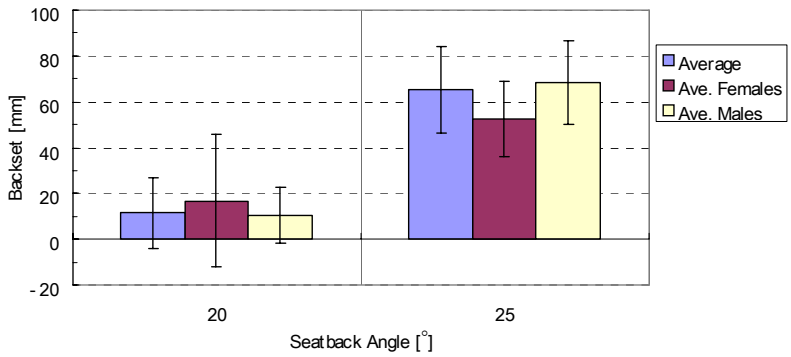

Fig.3 Average and standard deviation of the backsets measured during initial condition

VOLUNTEERS

6 adult males and 3 adult females were chosen as volunteers for the tests. Table 1 shows the physical information of volunteers. Tests with cineradiography measurements were conducted only using the male volunteers. The consent of the volunteers was obtained before testing commenced. The test protocol was subjected to the approval of the Special Committee of Ethics, Medical Department, University of Tsukuba.

Table 1. Details of the volunteers

Volunteer ID	Age [Year]	Sex	Height [cm]	Weight [kg]	Sitting height [cm]
I	23	F	164	50	85
II	22	F	160	45	86
III	24	F	162	46	85
IV	22	M	172	69	86
V	25	M	173	70	90
VI	24	M	176	65	94
VII	26	M	166	61	89
VIII	24	M	172	64	90
IX	25	M	172	67	92

ANALYTICAL METHODS

ANALYTICAL METHOD OF THE HEAD/NECK/TORSO BEHAVIOR

Coordinate system : An absolute coordinate system, as shown in Fig.1, was used for analyzing the head/neck/torso behavior. Positive values of the X-axis and the Z-axis indicate the forward direction and downward direction respectively. In addition, counter clockwise rotation around Y-axis was set as positive.

Physical quantities representing the head/neck/torso behavior : The head displacement and rotation angle were calculated as physical quantities representing the head behavior. The head behavior relative to upper torso was obtained by calculating the head displacement and rotation relative to the T1. The neck rotation relative to the T1 and head rotation relative to the neck were calculated as physical quantities representing the relative neck behavior. The T1 displacement and rotation were calculated as physical quantities of the upper torso behavior. Moreover, In order to determine the torso extension during the impact, the change in distance between the T1 and the hip point was calculated.

ANALYTICAL METHOD OF CERVICAL VERTEBRAL MOTION

Template of the cervical vertebra and coordinate systems : A template of the cervical vertebra for each volunteer was created from an x-ray image of each volunteer's cervical vertebra (Fig.4). The cervical vertebral motion was determined by superimposing the template over the sequential images from the cineradiography. Fig.5 shows the outer edge of the facet joint and the local coordinate system utilised.

Physical quantities representing the vertebral body motion : The vertebral rotation relative to the C7 and the lower vertebra were calculated as physical quantities representing the relative rotation between the vertebrae. The vertebral displacement relative to the C7 and the lower vertebra were also calculated to represent the shear between the vertebrae. The vertebral rotation and the vertebral displacement relative to the C7 were defined respectively as the rotation and the displacement of the lower edge midpoint of the local coordinate system of each vertebra relative to the local coordinate system of the C7. The vertebral rotation and displacement relative to the lower vertebra were defined respectively as the rotation and displacement of the lower edge midpoint of the local coordinate system of each vertebra relative to the local coordinate system of vertebra located directly below. Also the vertebral displacement relative to the lower vertebra was normalized by the linear distance of the lower edge anterior point and the posterior point of the lower vertebra. A positive value represented flexion, forward displacement and downward displacement.

Physical quantities representing the facet joint behavior : Because it was impossible to measure the facet joint strains directly, the front/rear edge strain and the shear strain of the facet joint, as shown in Fig.6, were calculated as physical quantities representing the facet joint behavior. These strains were assumed to be equivalent with the strains caused by the facet joint capsule deformation. In addition, positive values represented tensile strain and rearward shear strain.

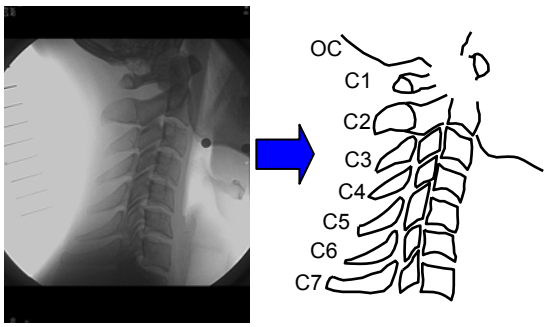

Fig.4 Template of the cervical vertebrae

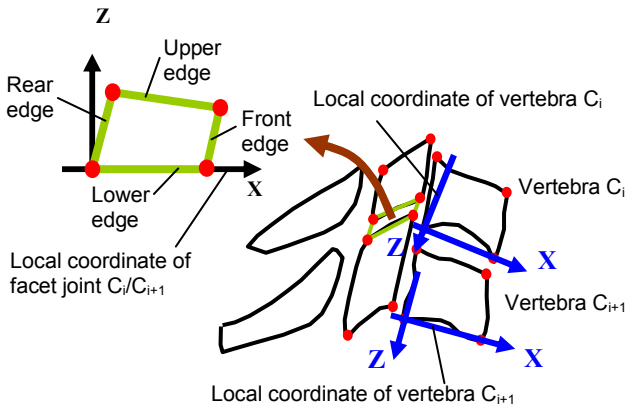

Fig.5 Local coordinate systems of the vertebra and facet joint

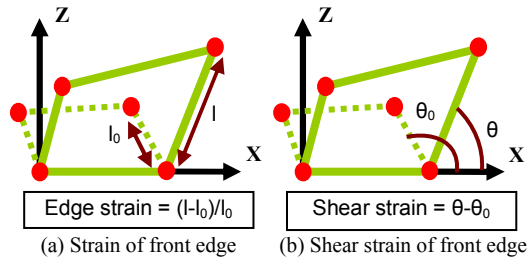

Fig.6 Strains representing the facet joint behavior

ANALYTICAL METHOD OF IMPACT FORCES ACTING ON HEAD/NECK

The head motion was assumed to be the 2-dimensional motion of a rigid body. The origin of head coordinate system was defined as the anatomical center of gravity of the head (Beier et al., 1980); located at a point which was 5mm in front of the ear hole on the Frankfurt line and 20mm perpendicular to this line. The X-axis was parallel to the Frankfurt line and Z-axis was perpendicular to X-axis (Fig.7). The acceleration responses of the head, and axial forces, shear forces, bending moments acting on the upper neck were determined from the values taken by the accelerometer and velocimeter placed in the subject's mouth and also by the values measured by the strain gauges attached on the head restraint pole.

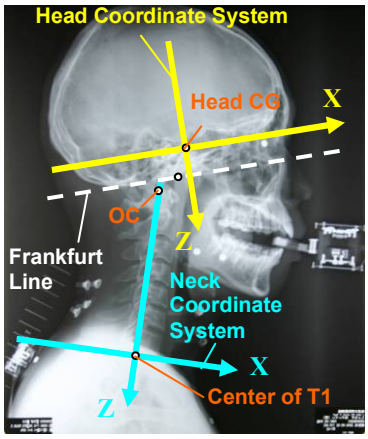

Fig.7 Definition of the Head and T1 Coordinate System

RESULTS

THE HEAD/NECK/TORSO BEHAVIOR AND THE CERVICAL VERTEBRAL MOTION IN A MASS PRODUCTION CAR SEAT ENVIRONMENT

The head/neck/torso behavior (Fig.8) and the cervical vertebral motion (Fig.9) during the impact were divided into the first phase; when the volunteer's body was sinking into seat, and the second phase; when the volunteer's body was rebounding forward. In this paper, the average results of the male volunteers for tests with a seat back angle of 25°, a sled acceleration 40m/s^2 and a relaxed muscle condition are presented.

First phase of the impact (0ms to 130ms) :

The upper torso contacted the seat back after 85ms and the head contacted the head restraint approximately 10ms later (Fig.10(a)). The head and the upper torso moved rearward as the head restraint and the seat back cushioned the impact (Fig.10(a)). Therefore, it was found that the head flexed relative to the upper torso (Fig.10(c)). Extension of the head began at 110ms (Fig.10(c)). The rearward displacement of the head and the T1 reached a maximum value at 130ms (Fig.10(a)). In addition, the extension of the upper torso also reached a maximum at this time (Fig.10(c)).

From the average results of each of the vertebral bodies' behavior relative to the C7, it was found that the C0 to the C6 began to flex due to the contact between the upper torso and the seatback (Fig.11(c)). The flexion angle was found to increase in the upper vertebrae relative to the C7. The C0 to the C6 also sheared forward relatively to the C7 (Fig.11(a)). In addition, the C0 and the C1 moved relatively upward, but the other vertebral body moved relatively downward (Fig.11(b)).

From the average results of the strains of the facet joint, forward shear strains occurred on the C5/C6 and backward shear strains occurred on the C2/C3 to the C5/C6 at 100ms (Fig.12(c)). Moreover, the tensile strain also occurred on the C2/C3 to the C5/C6 and compression strain was found to occur on the C6/C7 at the same time (Fig.12(a) and Fig.12(b)).

Second phase of the impact (130ms to 200ms) :

The head and the upper torso were found to move forward after 130ms due to the rebound of the head and upper torso from the seat (Fig.10(a)). The head extended to a maximum at 150ms, then began to flex (Fig.10(c)). The upper torso left contact from seatback at 165ms and head left the head restraint 15ms later (Fig.10(a)). This phenomenon called "differential rebound" was also confirmed in low speed rear-end impact tests on human cadavers (Sundararajan et al., 2004).

From the average results of each vertebra's behavior relative to the C7, it was found that the inclination of the flexion angle of the C0 to the C4 increased with the rebound of the head from head restraint (Fig.11(c)). At 150ms, the C6 angle changed from flexion to extension and the inclination of the flexion angle of the C0 to the C3 increased (Fig.11(c)). At 165ms, the C4 and C5 angle changed from flexion to extension and the inclination of the flexion angle of the C0 to the C3 increased again (Fig.11(c)). Moreover, the C0 to the C6 also changed from forward shear to rearward shear (Fig.11(a)), the C0 and the C1 also changed from upward displacement to rearward displacement at this time (Fig.11(b)). The flexion angle of the C0 to the C3 reached a maximum at 180ms (Fig.11(c)).

From the average results of strains on the facet joint, the strain on the C5/C6 changed from tension to compression at 150ms and tensile strain on the C2/C3 to the C4/C5 began to decrease at 180ms (Fig.12(a) and Fig.12(b)). The shear strain on the C4/C5 to the C6/C7 changed from rearward to forward at 165ms (Fig.12(c)).

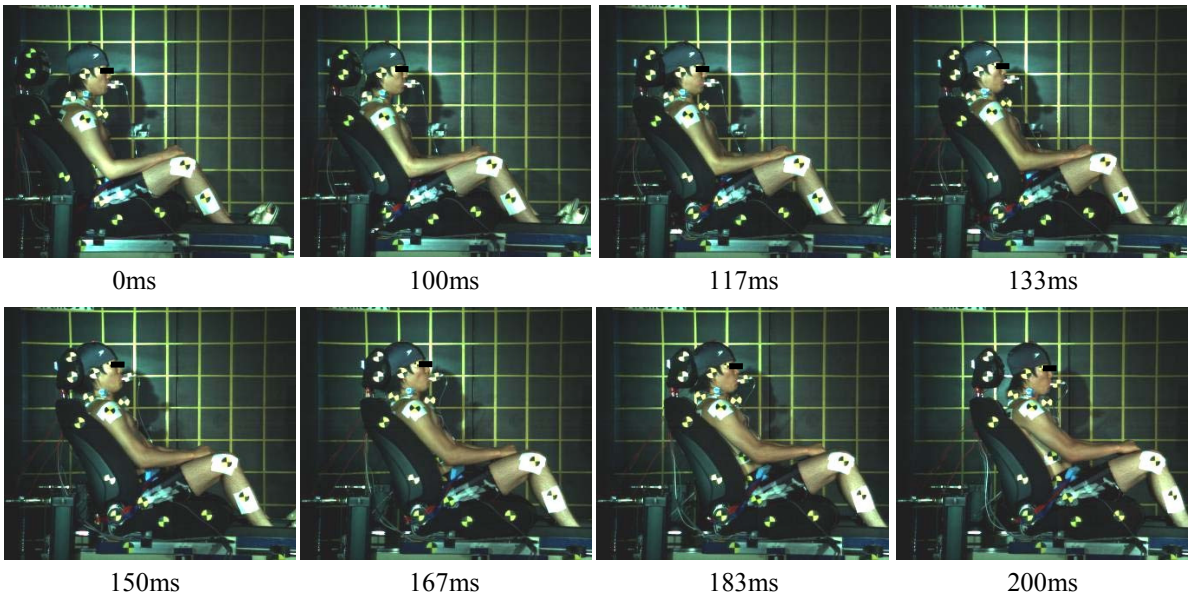

Fig.8 Sequential photographs of the head/neck/torso behavior during impact

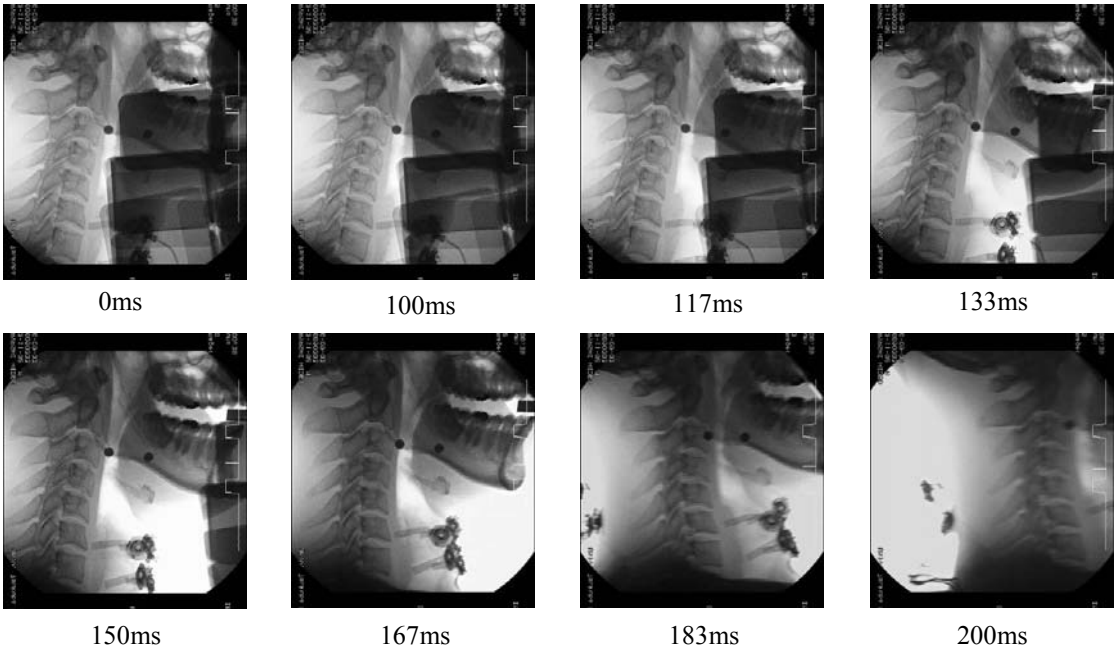

Fig.9 Sequential cineradiography images of the vertebral motion during impact

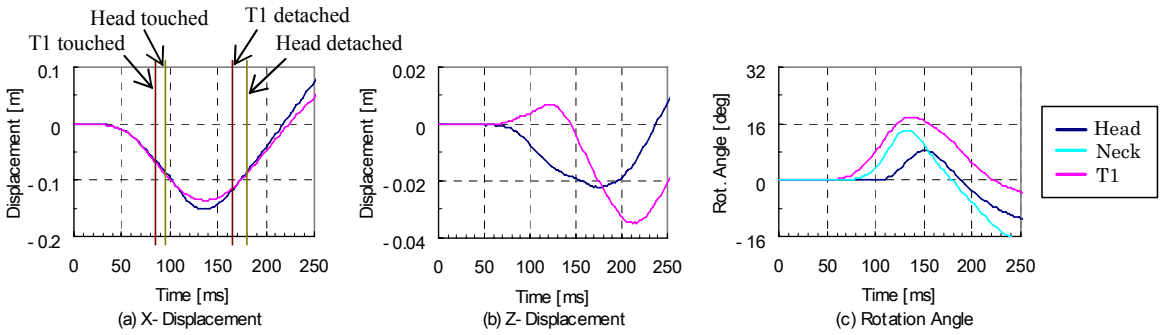

Fig.10 Displacement and rotation of the head/neck/torso during impact

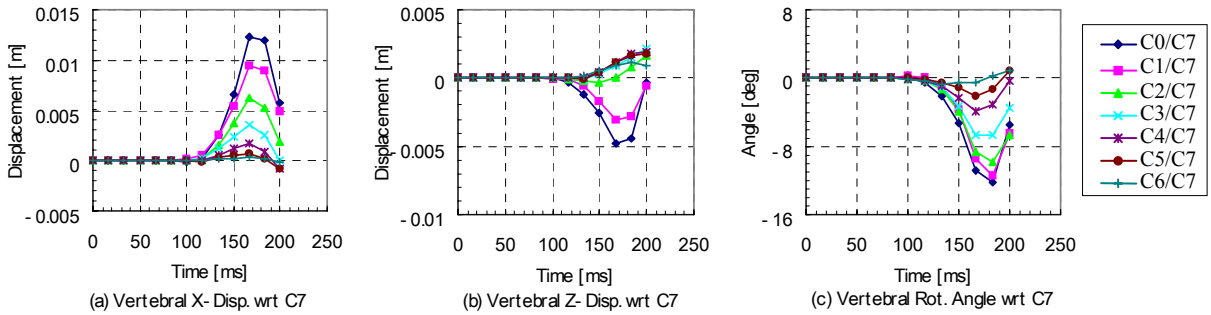

Fig.11 Displacement and rotation of the vertebrae wrt the C7 during impact

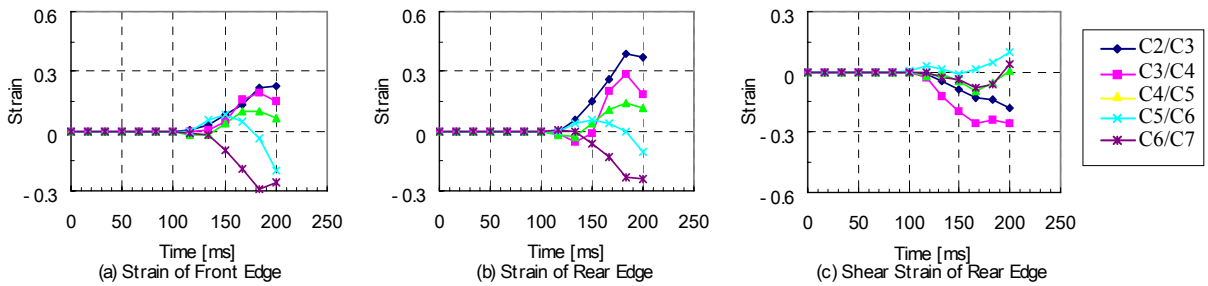

Fig.12 Strain and shear strain of the facet joints during impact

In addition, the head displacement and rotation angle relative to the T1, the head rotation angle relative to the neck, the neck rotation angle relative to the T1, and the change of the distance between the T1 and the hip point are shown in Fig.13. Vertebral displacement and the rotation angle relative to the lower vertebra are shown in Fig.14.

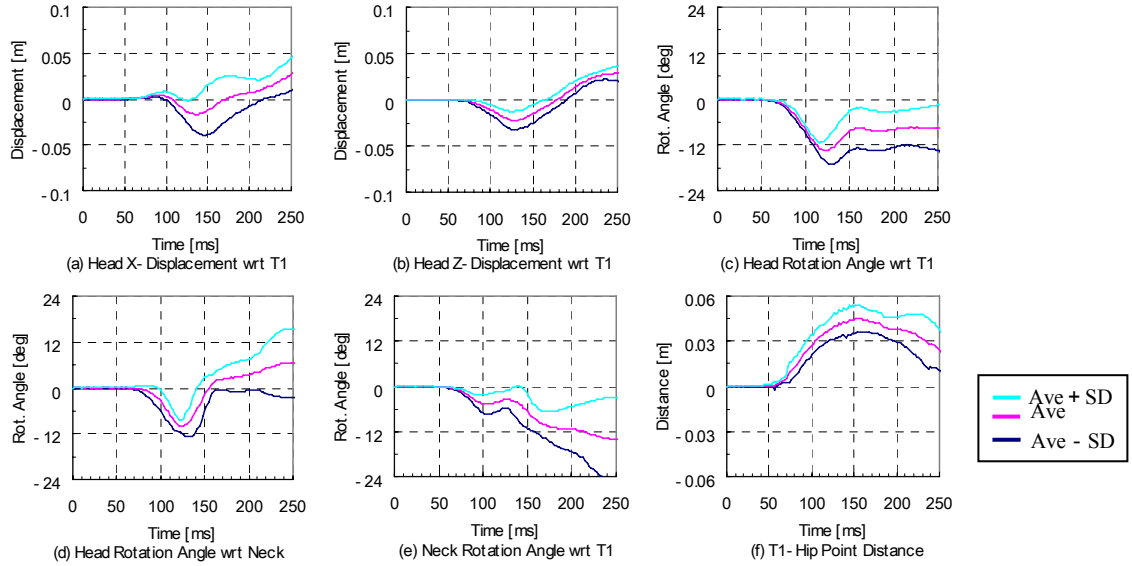

Fig.13 Relative displacement and rotation of the head/neck/torso during impact

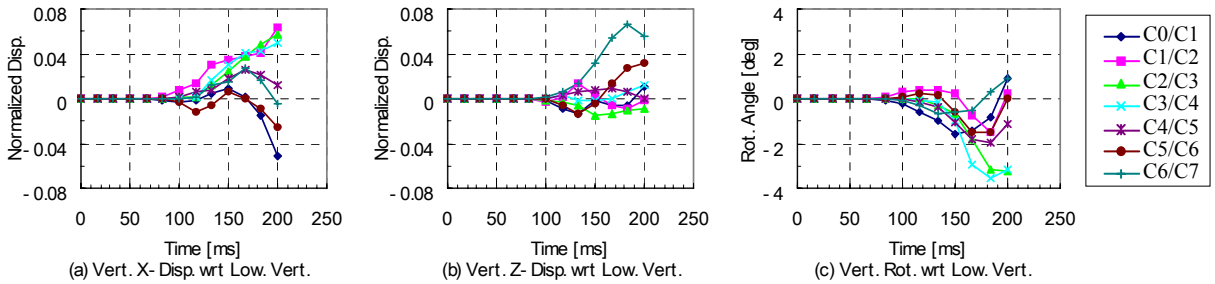

Fig. 14 Relative disp. and rotation of the vertebrae wrt the lower vertebra during impact

THE EFFECT OF GENDER DIFFERENCE ON THE HEAD/NECK/TORSO BEHAVIOR

As a result of the comparison of the average head/neck/torso behavior between males and females under same impact conditions, it was found that females have a larger head rearward displacement relative to the T1 compared to males as shown in Fig.15(a) ($p<0.1$). Furthermore, females were also found to have a greater head flexion angle relative to the neck compared with males as shown in Fig.15(b) ($p<0.05$). Meanwhile, the error bars in the figure show the standard deviation (SD) of each parameter.

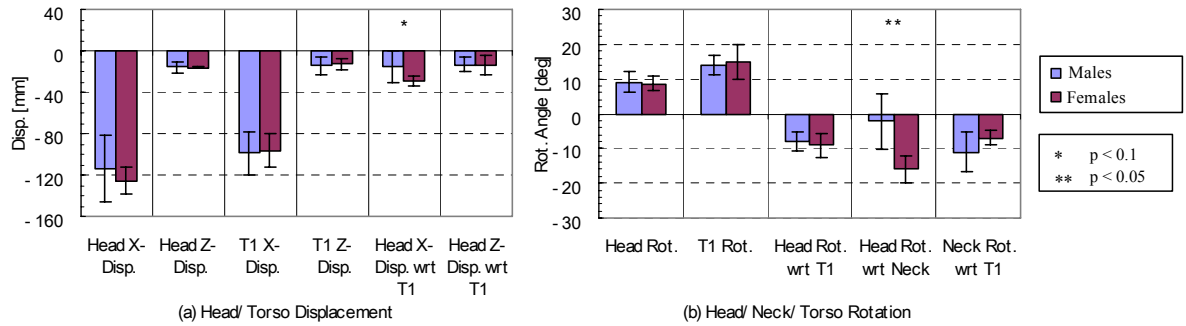

Fig.15 Comparison of the max. values of the parameters describing the average head/neck/torso behavior between male and female volunteers

EFFECT OF SEAT BACK ANGLE DIFFERENCE

The maximum value of the average head/neck/torso behavior and the average cervical vertebral motion between seat back angles of 20° and 25° under same sled acceleration and muscle condition were compared and the following results were obtained.

Head/neck/torso behavior :

The head and the T1 rearward displacement was smaller when the seat back angle was 20° compared to 25°, as shown in Fig.16(a) ($p<0.05$). Moreover, the head and the T1 extension angle, and the head flexion angle relative to the neck were restrained significantly when the seat angle was 20°, as shown in Fig.16(b) ($p<0.05$).

Cervical vertebral motion :

Since the C2 and the C3 flexion angles relative to lower vertebra were smaller when seat back angle was 20° (Fig.17(a)), the tensile strain on the rear edge of the C2/C3 and the C3/C4 facet joint also decreased (Fig.17(a)). Furthermore, because the C5 and the C6 extension angle relative to the lower vertebra were small (Fig.17(b)) and their rearward displacements are also small (Fig.17(c)), compression strain on the rear edge of the C5/C6 and the C6/C7 facet joint was better restrained when the seatback angle was 20°, as shown in Fig.18(b) (C5/C6: $p<0.1$). Despite forward shear strain on the upper vertebrae facet joint was increasing, (Fig.18(c)) due to an increase in the upper vertebrae forward shear relative to lower vertebra, as shown in Fig.17(c) (C3/C4: $p<0.1$), the rearward shear strain on the C5/C6 and the C6/C7 facet joint were restrained (Fig.18(d)) due to the decrease of the C5 and the C6 rearward shear relative to the lower vertebra as shown in Fig.17(d) (C5/C6: $p<0.1$).

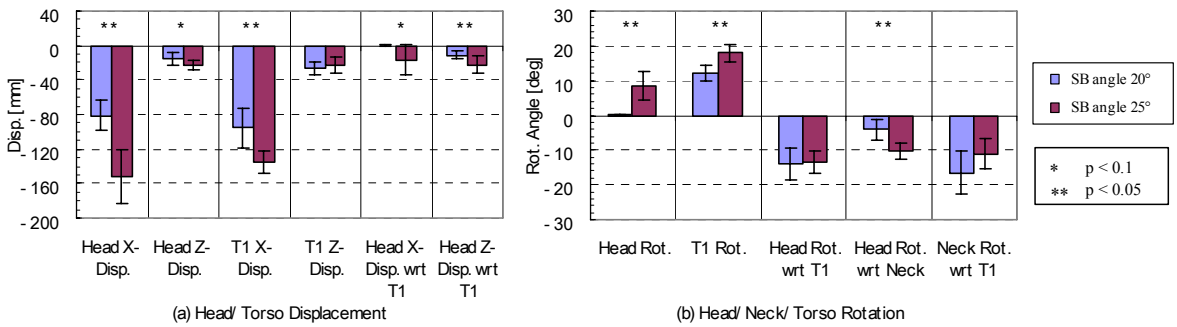

Fig.16 Comparison of the max. values of the parameters describing the average head/neck/torso behavior between seatback angles of 20° and 25°

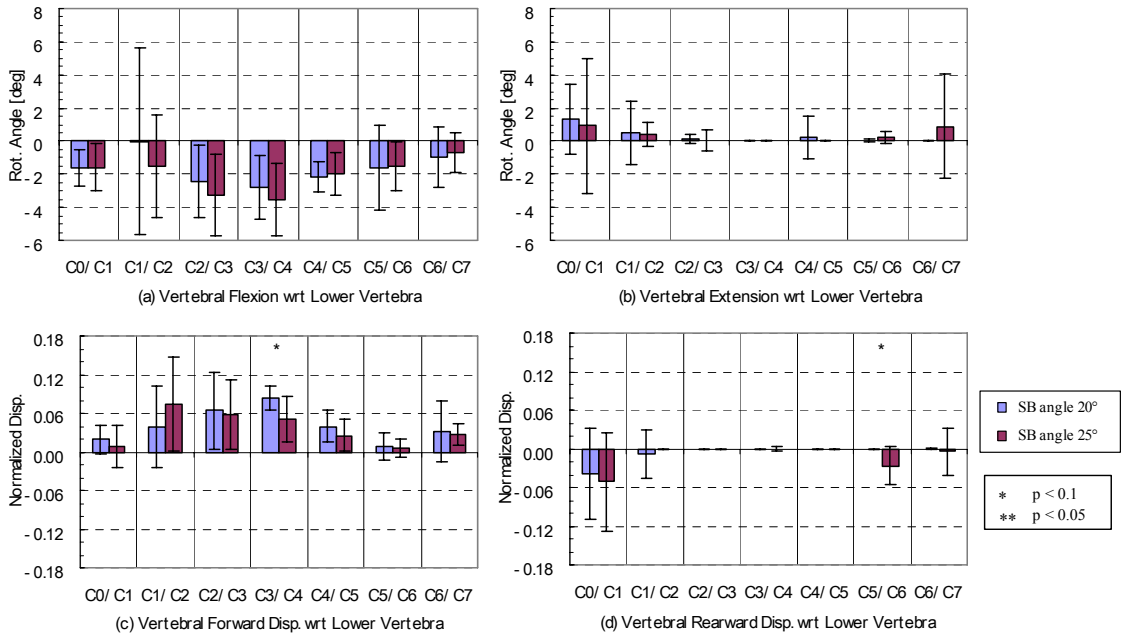

Fig.17 Comparison of the max. values of the parameters describing the average vertebral motion between seatback angles of 20° and 25°

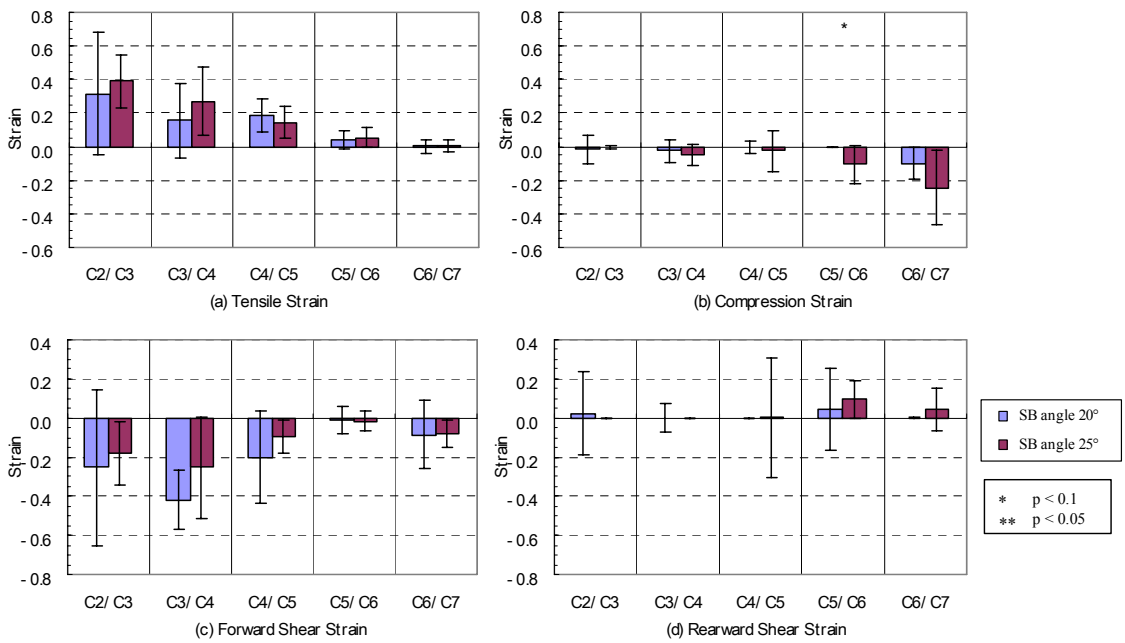

Fig.18 Comparison of the max. values of the parameters describing the average facet joint strains between seatback angles of 20° and 25°

EFFECT OF SLED ACCELERATION MAGNITUDE

The maximum value of the average head/neck/torso behavior and the average cervical vertebral motion between a sled acceleration of 33m/s^2 and 40m/s^2, under same seat angle and muscle conditions, were compared and the following results were obtained.

Head/neck/torso behavior :

The head ($p<0.1$) and the T1 ($p<0.05$) rearward displacements when the sled acceleration was 40m/s^2 were found to be greater than when the sled acceleration was 33m/s^2 (Fig.19(a)). Moreover, the T1 extension angle ($p<0.05$), the head flexion angle relative to the T1 ($p<0.05$) and the head flexion angle relative to the neck ($p<0.1$) indicated a similar tendency (Fig.19(b)).

Cervical vertebral motion :

As the sled acceleration increased, the flexion angle of the C0, and the C2 to C4 relative to the lower vertebra increased as shown in Fig.20(a) (C0/C1: $p<0.1$). The C5 rearward displacement relative to the C6 also increased, as shown in Fig.20(d). Therefore, the tensile strain on the rear edge of the C2/C3 to the C4/C5 facet joint and the compression strain on the rear edge of the C5/C6 ($p<0.1$) increased (Fig.21(a) and Fig.21(b)). However, the difference between the compression strain on the C6/C7 facet joints was not significant (Fig.21(b)). Furthermore, when the sled acceleration was 40m/s^2 the rearward shear strain on the C5/C6 facet joint increased (Fig.21(d)) due to an increase in the C5 rearward displacement relative to the C6 (Fig.20(d)).

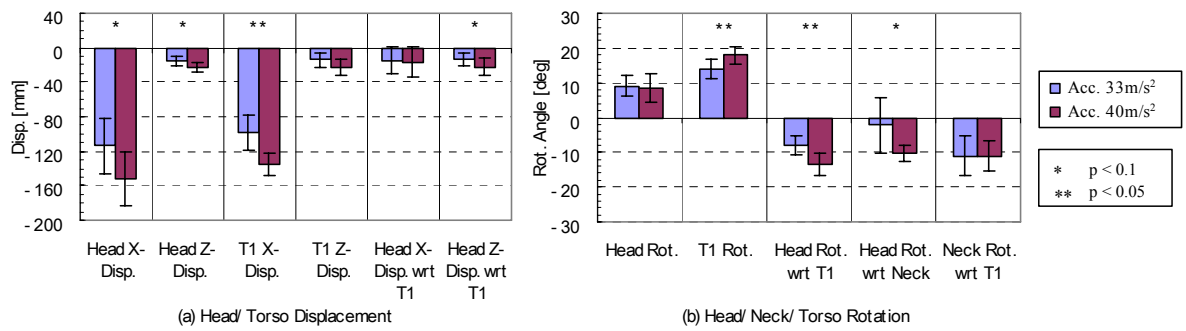

Fig.19 Comparison of the max. values of the parameters describing the average head/neck/torso behavior between sled acc. of 33m/s^2 and 40m/s^2

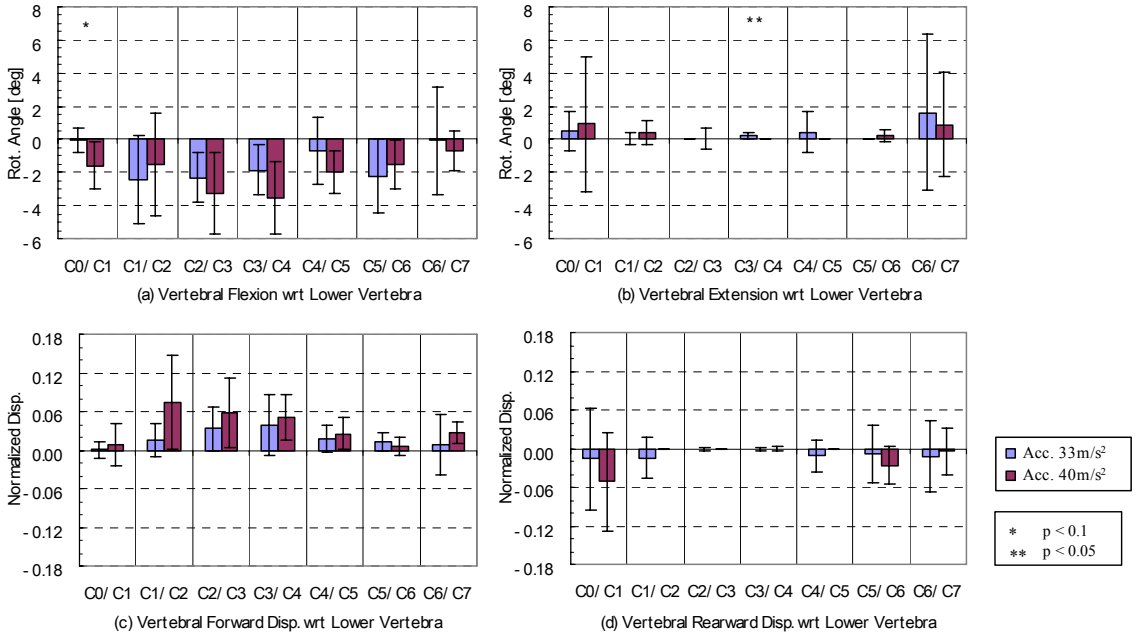

Fig.20 Comparison of the max. values of the parameters describing the average vertebral motion between sled acc. of 33m/s^2 and 40m/s^2

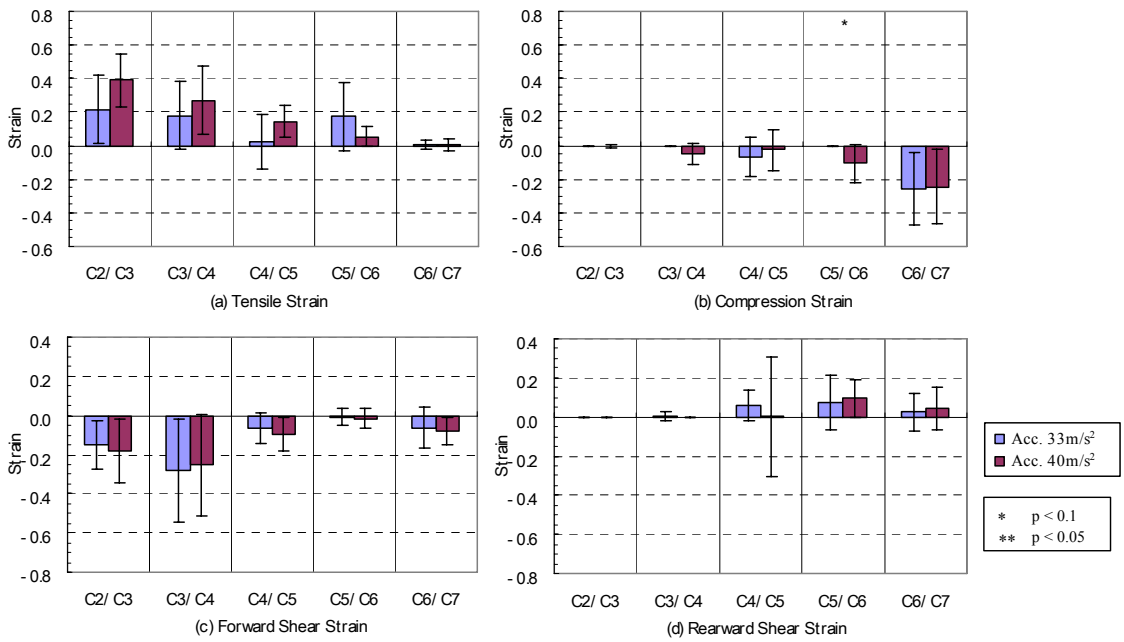

Fig.21 Comparison of the max. values of the parameters describing the average facet joint strains between sled acc. of 33m/s^2 and 40m/s^2

EFFECT OF THE MUSCLE CONDITION

The maximum value of the average head/neck/torso behavior and the average cervical vertebral motion between relaxed and tensed muscle conditions, under same seat angle and sled acceleration, were compared and the following results were obtained.

Head/neck/torso behavior :

Comparing the results between relaxed and tensed muscle conditions, it was found that there were no significant differences on the rearward displacement and the upward displacement of the head and the T1 (Fig.22(a)). However, the head extension angle increased ($p<0.1$) in the tensed muscle

condition, although it was also found that the head flexion angle relative to the T1, the head flexion angle relative to the neck and the neck flexion angle relative to the T1 were significantly restrained ($p<0.05$) (Fig.22(b)).

Cervical vertebral motion :

In the tensed muscle condition, the tensile strain on the rear edge of the C2/C3 to the C5/C6 facet joints were significantly restrained as shown in Fig.24(a) (C2/C3 and C4/C5: $p<0.05$, C5/C6: $p<0.1$) due to the decrease in flexion angle of the C2 to the C5 relative to the lower vertebra as shown in Fig.23(a) (C2/C3 and C4/C5: $p<0.05$, C3/C4: $p<0.1$). However, because the extension angle (C4/C5: $p<0.05$) and the rearward displacement of the C4 to the C6 relative to lower vertebra increased (Fig.23(b) and Fig.23(d)), there was nearly no restrictive effect in the compression angle on the rear edge of the C4/C5 to the C6/C7 facet joints. Conversely compression strain on the rear edge of the C4/C5 and the C5/C6 facet joints showed a tendency to increase (Fig.24(b)). Furthermore, in the tensed muscle condition, the forward shear strain on the C2/C3 to the C6/C7 facet joints decreased (Fig.24(c)) along with a decrease of the C1 to the C6 forward displacement relative to lower vertebra as shown in Fig.23(c) (C2/C3: $p<0.1$, C6/C7: $p<0.05$), though rearward shear strain on the C4/C5 to the C6/C7 increased (Fig.24(d)) due to the increase of the C4 to the C6 rearward shear relative to lower vertebra (Fig.23(d)).

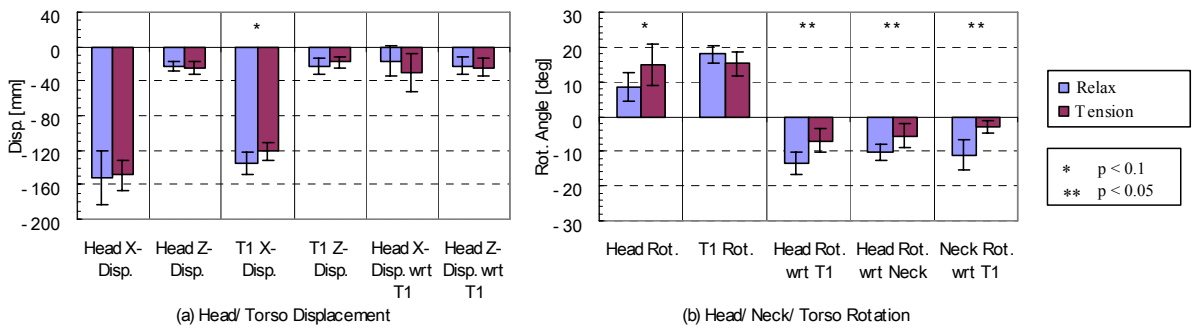

Fig.22 Comparison of the max. values of the parameters describing the average head/neck/torso behavior between the relaxed and tensed conditions

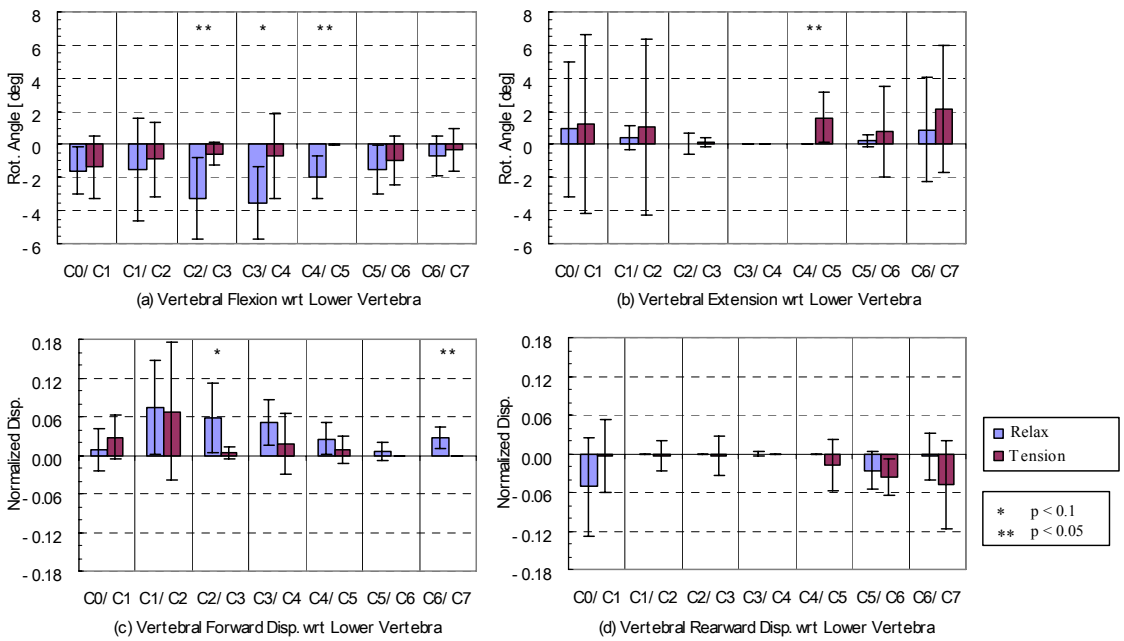

Fig.23 Comparison of the max. values of the parameters describing the average vertebral motion between the relaxed and tensed conditions

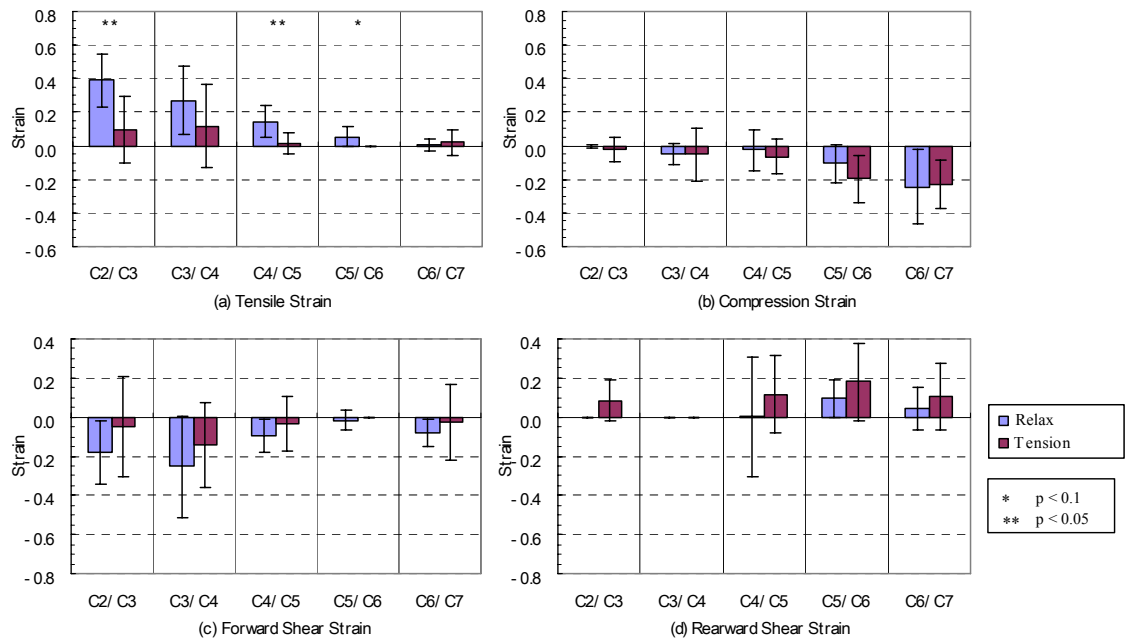

Fig.24 Comparison of the max. values of the parameters describing the average facet joint strains between the relaxed and tensed conditions

DISCUSSION

THE HEAD/NECK/TORSO BEHAVIOR AND THE CERVICAL VERTEBRAL MOTION CHARACTERISTIC

In the tests using a rigid seat without a head restraint, the imposition on torso by the rigid seat back and the inertial force acting on head caused flexion in the upper vertebrae and extension in the lower vertebrae, resulting in an S-shape curve of cervical vertebrae (Ono et al., 1997). In this study, since the upper torso sunk into the seat back and the head motion was restrained by the head restraint, a relative flexion occurred in almost all vertebrae. Moreover, ramping up by seat back caused a compression force on the intervertebral joint. It was assumed that the stiffness of intervertebral joint tend to decrease due to the compression force (Yang et al., 1997) and it might have caused the shear on the C2/C3 and the C5/C6.

In the second phase, the spine straightened and the head moved upward, so the acting point of the head restraint reaction force became lower than the OC (Occipital Condyles). Therefore, despite the head extension, the upper vertebrae showed relative flexion and forward shear behavior. Furthermore, the forward displacement made progress from the lower vertebrae, causing a rearward shear in the C4/C5 and the C5/C6, and a large extension in the C6 relative to the C7. Consequently, the tensile strain occurred on facet joints of the upper vertebrae and the compression strain occurred on the C6/C7 facet joint.

DIFFERENCES ON THE HEAD/NECK/TORSO BEHAVIOR DUE TO GENDER DIFFERENCE

Males have bigger cervical skeletal geometry and also the head moment of inertia is greater compared to females. This caused a flexion moment increase during the first phase of the impact, so the neck extension angles of the male volunteers were smaller when compared to the female volunteers. Moreover, another possible reason is that males are sinking into the seat back more than females due to being heavier. Van de Kroonenberg et al. (1998) reported that sinking more into seat back restrained the T1 acceleration, causing a decrease in head acceleration.

DIFFERENCES ON THE HEAD/NECK/TORSO BEHAVIOR AND THE CERVICAL VERTEBRAL MOTION DUE TO THE SEAT BACK ANGLE DIFFERENCE

As also reported by Latchford et al. (2005), the linear distance between the head and the head

restraint (backset), and between the upper torso and the seat back in the initial condition tended to increase along with an increase of the seat back angle. As a result, if seat back angle is increased, it could be said that the rearward displacement of the head and the T1 would also increase. Furthermore, during the test condition using a small seatback angle, before the head extension occurred, the head collided against the head restraint first and then rebounded. Therefore, the extension behavior of the head was restrained significantly.

During the test condition when the seat back angle was 20°, the compression strain on the rear edge of the C5/C6 and the C6/C7 facet joints also decreased. This was caused by a decrease in the rearward shear and the extension of the lower vertebrae along with a decrease of the head rearward displacement. The decrease of the lower vertebrae extension angle due to a small backset corresponded well with the result of a simulation conducted, using the head/neck model of MADYMO by Stemper et al. (2006).

DIFFERENCES ON THE HEAD/NECK/TORSO BEHAVIOR AND THE CERVICAL VERTEBRAL MOTION DUE TO AN IMPACT LEVEL DIFFERENCE

As the sled acceleration increased, it was found that the impact forces acting on the volunteers also increased, causing an increase in almost all parameters representing the head/neck/torso behavior. However, the head extension angles of both conditions were nearly the same due to the limitation of the head restraint.

The flexion moment on the upper neck caused by the reaction force from the head restraint increased along with an increase of the sled acceleration. Therefore, the flexion angle of the upper cervical vertebrae increased, causing a subsequent increase in the tensile strain on facet joint. Furthermore, due to an increase in the impact force spreading from the T1 to a higher cervical vertebra, the rearward shear and extension of the C5 relative to the C6 also increased. As a result, the compression strain on the rear edge of the C5/C6 facet joint increased, following the compression strain on the C6/C7 facet joint.

DIFFERENCES ON THE HEAD/NECK/TORSO BEHAVIOR AND CERVICAL VERTEBRAL MOTION DUE TO THE MUSCLE CONDITION

The rotational motion of the neck and the T1 were significantly restrained in the tensed muscle condition. It was observed that the muscle forces limited the neck and the T1 motion. Moreover, the head restraint limitation caused nearly no differences on the rearward displacement of the head.

In the tensed muscle condition, the neck could be assumed to be one rigid link, therefore the relative motion between the vertebrae decreased significantly. As a result, the flexion angle and the forward displacement of each vertebra relative to the lower vertebra decreased, restraining the tensile strain and the forward shear strain of the middle vertebra facet joint. However, the boundary of the stiffness change on the connection region (joint) between neck and the torso caused the C5/C6 and the C6/C7 to become relatively susceptible to loading. Therefore, the restrictive effect of the muscle forces on the compression strain on the rear edge of this vertebrae facet joint was not significant.

RISK POSSIBILITY OF NECK INJURIES IN MASS PRODUCTION CAR SEATS

In previous research, the data obtained from tests with human volunteers using rigid seats were analyzed to determine the cervical vertebral motion using the same method as in this study. We established injury risk thresholds using the strains on the facet joints by weighing the sense of discomfort after tests and strains on facet joints during the impact (Ono et al., 2006). Here, we evaluated strains on the facet joints of each volunteer during tests with mass production car seats by the thresholds.

Fig.25 shows the strain and the shear strain on the front edge and on the rear edge of the C2/C3 to the C6/C7 facet joints of each of the volunteers, plotted at 16.7ms intervals. Dashed lines inside the figure indicate the thresholds of each facet joint strain.

All of the strains exceeding the thresholds were shear strain. It could be said that the compression strain and the tensile strain on the facet joints could be reduced using mass production car seats. However, there are some cases when the shear strain came close or exceeded the thresholds. In other words, although the average backset was short, or during the tensed condition when the neck motion was restrained, the risk possibility of a neck injury could be higher if the interaction condition between

the occupant's head/neck/torso and the seat were not controlled appropriately.

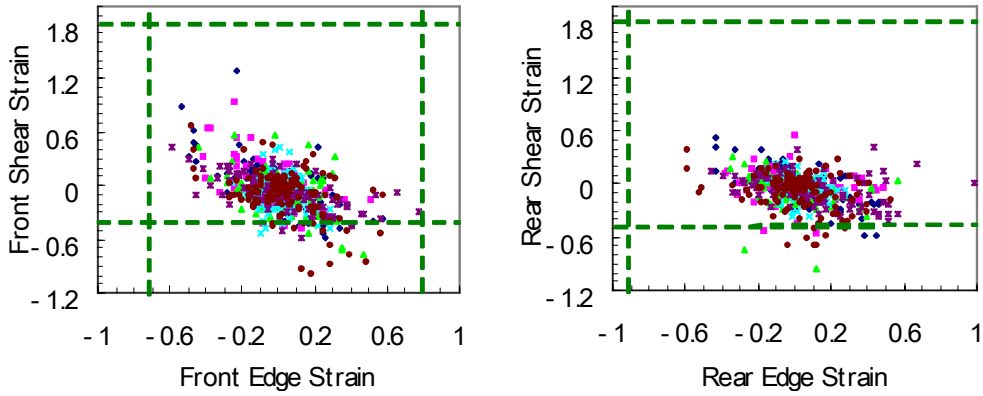

Fig.25 Comparison between the facet joint strains and the injury threshold

In this study, it was found that the visual head/neck/torso motion was suppressed by the motion limitation of the head restraint and seatback. However, high magnitudes of strains on certain facet joints were observed, showing that the relative motion between cervical vertebrae was not sufficiently depressed. In other words, it was difficult to predict or assess the occurrence of neck injuries based only on the visual head/neck/torso behavior. Development of a neck injury criteria and assessment based on the cervical vertebral motion is essential.

It can also be assumed that the differences on the interaction effect between the head/neck/torso and the seat influenced the risk of neck injury. Therefore, diversity in seating posture, occupant's body size, gender, etc should be taken into consideration during the design and development or the safety assessment of vehicle seats.

LIMITATIONS OF THE STUDY

In this study, the number of volunteers was small (6 males and 3 females). Thus, there was a lack of test data for universalizing the result of this study. Furthermore, since it was impossible to conduct tests with the impact level that would probably trigger a neck injury, it is difficult to predict the cervical spine motion which would cause a neck injury based on the results of this study.

CONCLUSION

By conducting low speed rear impact tests on human volunteers using a horizontal mini-sled apparatus with a mass production car seat, and by analyzing the head/neck/torso and the cervical vertebral motion during the impact, the following conclusions were made.

- In the first phase of the impact, since the upper torso sunk into the seat back and the head motion was restrained by the head restraint, the relative flexion occurred in almost all vertebrae. In the second phase of the impact, due to the reaction force from the head restraint and the forward motion of the upper torso, high magnitudes of tensile strain and compression strain occurred on facet joints of the upper vertebrae and the C6/C7 respectively.
- With a small seat back angle, the rearward displacement and the extension angle of the head were restrained; causing a decrease in the compression strain on facet joints of lower vertebrae. However, the tensile strain on facet joints of the upper vertebrae showed a tendency to increase.
- Although the impact level increased, the head flexion angle did not increase due to the head restraint limitation. However, the strain on the facet joint increased along with an increase in the impact level.
- In tensed muscle condition, the head displacement, the T1 displacement and the neck rotation decreased, restraining the motion of the middle vertebrae. However, the compression strain on the facet joint of the C6/C7 did not decrease significantly. Conversely the compression angle on the C5/C6 facet joint tend to increase.

- The neck extension of female subjects tends to increase in comparison to the males under the same test conditions.
- By comparing with the previous experimental results using a rigid seat, the compression strain and the tensile strain of facet joints were reduced significantly. But, in certain damping conditions between the occupant's head/torso and the seat, the shear strain on facet joints of upper vertebrae increased, indicating the possibility of increasing the risk of neck injuries developing.

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REFERENCES

Eis V., Sferco R., and Fay P., A Detailed Analysis of The Characteristics of European Rear Impacts, Proceeding of the 19th ESV Conference, Washington D.C., Paper No. 05-0385, 2005

Beier G., Schuller E., Schuck M., Ewing C.L., Becker E.D., and Thomas D.J., Center of Gravity Moments of Inertia of Human Heads, Proceedings of International IRCOBI Conference Biomechanics of Impacts, 1980, 218-228

Brault J.R., Wheeler J.B., Siegmund G.P., and Brault E.J., Clinical Response of Human Subjects to Rear-End Automobile Collisions, Arch Phys Med Rehabil 79, 1998, 72-80

Dehner C., Elbel M., Schick S., Walz F., Hell W., and Kramer M., Risk of injury of the cervical spine in sled tests in female volunteers, Clinical Biomechanics 22, 2007, 615-622

Hernandez I.A., Fyfe K.R., Heo G., and Major P.W., Kinematics of Head Movement in Simulated Low Velocity Rear-End Impacts, Clinical Biomechanics 20, 2005, 1011-1018

Kleinberger M., Voo L., Merkle A., Bevan M., Chang S., and McKoy F., The Role of Seatback and Head Restraint Design Parameters on Rear Impact Occupant Dynamics, Proceedings of the 18th International Technical Conference on the Enhanced Safety of Vehicles, Paper No. 229, 2003

Latchford J., Chirwa E.C., Chen T., and Mao M., The Relationship of Seat Backrest Angle and Neck Injury in Low-Velocity Rear Impacts, Proc. IMechE Vol.219 Part D: J. Automobile Engineering, 2005, 1293-1302

Mertz H.J., and Patrick L.M., Strength and Response of Human Neck, Proceedings of the 15th Stapp Car Crash Conference, SAE Paper 710855, 1971

Ono K, Ejima S., Suzuki Y., Kaneoka K., Fukushima M., and Ujihashi S., Prediction of Neck Injury Risk Based on the Analysis of Localized Cervical Vertebral Motion of Human Volunteers during Low-Speed Rear Impacts, Proceedings of International IRCOBI Conference Biomechanics of Impacts, 2006, 103-114

Ono K., and Kaneoka K., Motion Analysis of Human Cervical Vertebrae During Low-Speed Rear Impacts by The Simulated Sled, Crash Prevention and Injury Control, Vol.1, Issue 2, November 1999

Ono K., Kaneoka K., Wittek A., and Kajzer J., Cervical Injury Mechanism Based on the Analysis of Human Cervical Vertebral Motion and Head-Neck-Torso Kinematics During Low Speed Rear Impacts, Proceedings of the 41st Stapp Car Crash Conference Proceedings, SAE Paper 973340, 1997

Ono K. and Kanno M., Influences of The Physical Parameters on The Risk to Neck Injuries in Low Impact Speed Rear-End Collisions, Accident Analysis and Prevention 28(4), 1996, 493-499

Sawada M. and Hasegawa J., Development of A New Whiplash Prevention Seat, Proceeding of the 19th ESV Conference, Washington D.C., Paper No. 05-0288, 2005

Siegmund G.P., Brault J.R., and Wheeler J.B., The Relationship Between Clinical and Kinematic Responses from Human Subject Testing in Rear-End Automobile Collisions, Accident Analysis and Prevention 32, 2000, 207-217

Stemper B.D., Yoganandan N., and Pintar F.A., Effects of Head Restraint Backset on Head-Neck Kinematics in Whiplash, Accident Analysis and Prevention Vol.38, 2006, 317-323

Sundararajan S., Prasad P., Demetropoulos C.K., Tashman S., Begeman P.C., Yang K.H., and King A.I., Effect of Head-Neck Position on Cervical Facet Stretch of Post Mortem Human Subjects During Low Speed Rear End Impacts, Stapp Car Crash Journal, Vol.48, Paper No. 2004-22-0015, 2004

Tencer A.F., Mirza S.K., and Bensel K., The Response of Human Volunteers to Rear-End Impacts: The Effect of Head Restraint Properties, Spine 22, 2001, 2432-2442

van den Kroonenberg A., Philippens M., Cappon H., and Wismans J., Human Head-Neck Response During Low-Speed Rear End Impacts, Proceedings of the 42nd Stapp Car Crash Conference, SAE Paper 983158, 1998

Welcher J.B., Szabo T.J., Relationships Between Seat Properties and Human Subject Kinematics in Rear Impact Tests, Accident Analysis and Prevention Vol.33, 2001, 289-304

Yang K.H., Begman P.C., Muser M., Niederer P., and Waltz F., On The Role of Cervical Facet Joints in Rear End Impact Neck Injury Mechanisms. SAE SP-1226, Motor Vehicle Safety Design Innovations, SAE Paper 970497, 1997, 127-129.