PREDICTION OF NECK INJURY RISK BASED ON THE ANALYSIS OF LOCALIZED CERVICAL VERTEBRAL MOTION OF HUMAN VOLUNTEERS DURING LOW-SPEED REAR IMPACTS

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ABSTRACT

To clarify the mechanism that causes injury to the neck during rear-end collisions, the neck behavior of volunteer test subjects was carefully analyzed. As a result, stretch propagation was found to occur in soft tissue such as facet joint capsules, intervertebral discs and ligaments. The effects of gender and muscle condition on cervical vertebral motion were also revealed, and their respective roles in cervical injury risk were considered. Furthermore, the relation between the state of discomfort of volunteers after the experiments and the strain of intervertebral disc and facet joints indicated that it might be possible to estimate the risk of neck injury occurrence.

Keywords: Injury Criteria, Muscle, Gender, Neck, Volunteers, Whiplash

NECK INJURIES ARE MORE OFTEN caused by rear-end collisions than by any other type of automobile collision. Thus it is a pressing matter to determine the mechanism of injury occurrence. In low-speed rear-end collisions, the muscle tension before the impact is likely to affect the head and neck motions. In an earlier experiment, Ono and Kaneoka (1999) reported that the extension angle of the head decreased by about 30-40% when there is muscle tension in the neck. Mertz and Patrick (1967, 1971) reported that the muscle tension of the neck considerably reduced the extension rotation of the head during a rear-end collision. Neck injury evaluations made so far have generally set parameters in apparent visual motions of the neck and head that included considerations of conditions such as muscle tension. However, there has been no report concerning the effect of muscle tension on localized cervical vertebral motion. In addition, there were also cases where neck injury occured at a speed of 10 km/h or less (Eichberger et al., 1993, Kullgren et al., 2003).

In general, females are more susceptible to neck injury than males (Otermski et al., 1993). Lovsund et al. (1998) reported that the rate of neck injury occurrence in females was 20-40% higher than that of males. However, there was no report on what types of gender-based effects exist on torso and head motions, as well as cervical spine motions, during a collision.

It was reported that there is a relationship between pain and strain in joint capsules in low-speed rear-end collisions. Various studies have been made to determine the relationship between the occurrence of actual neck injury and the strain in joint capsules. Lu et al. (2005) reported that in an experiment using goats, pain occurred at a facet joint capsule strain of 47.2±9.6%.

Gibson et al. (2005) used a simulation to reproduce an actual automobile accident. They reported that based on the relationship between calculated facet joint capsule strain and actual degree of injury, the threshold value of the facet joint capsule strain to cause cervical injury was 40%. However, there is no research to evaluate the degree of strain which occurs around the cervical vertebrae at the time of impact.

Therefore, the present research examined the relationship between strain exerted on the intervertebral discs and facet joints of volunteer test subjects and the symptoms they exhibited after the experiment to verify the threshold for the occurrence of cervical injury.

METHODS OF EXPERIMENT

INERTIAL IMPACT LOADING ON THE HEAD IN A SIMULATED REAR-END COLLISION: The safety of the volunteers was of utmost concern; therefore, it was impossible to subject them to an impact load at a level that would cause injury. As a result, the authors investigated the collision continuance time and collision speed based on the results of a previous low-speed impact (Ono et. al., 1997) to design the impact load at a level that would guarantee the safety of the subjects.

An overview of the equipment used in the experiment is shown in Figure 1. In the experiment, a sled was attached to a roughly 2 m rail, and then the subject was seated in a rigid seat on the sled. A spring was attached to the end of the sled with hydraulically activated compression and released at a maximum impact speed of 6 km/h.

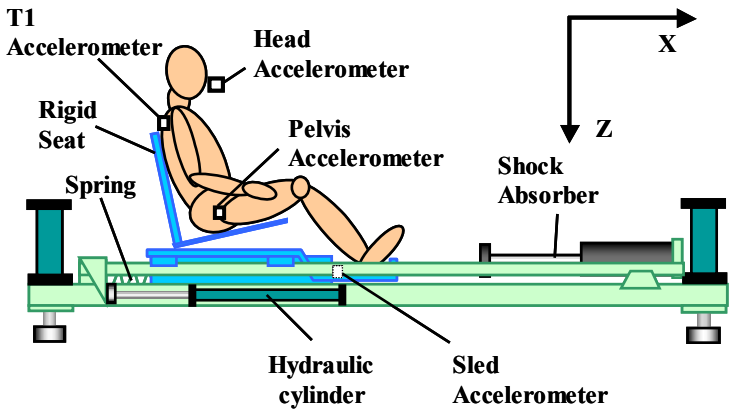


Figure 1. Outline of the sled test apparatus and coordinate system

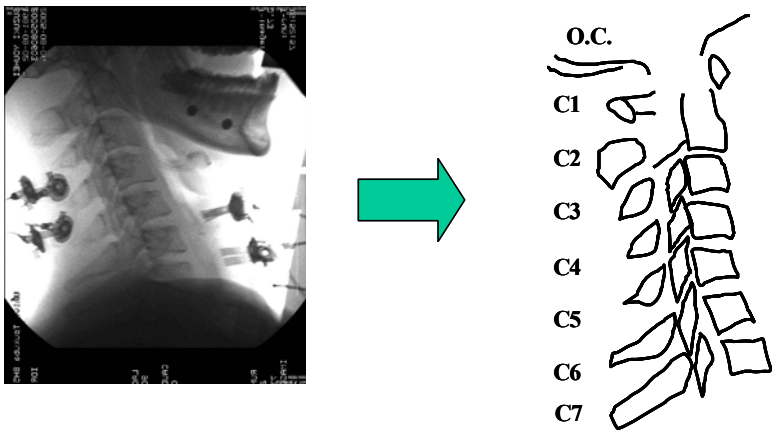
PHOTOGRAPHY OF HEAD/NECK MOTIONS USING A HIGH SPEED VIDEO CAMERA: In order to analyze the apparent visual motions of subjects' head/neck/torso during impact, a high-speed video camera with photographic capability of 500 frames/s was used. Based on the photographic images, the head/neck rotational angle and the displacement relative to the torso (the first thoracic vertebra T1) were calculated by tracing the motion of markers which were adhered to the subjects.

PHOTOGRAPHY OF CERVICAL VERTEBRAL MOTIONS USING CINERADIOGRAPHY: For the analysis of cervical vertebral motions during impact, a cineradiographic system (Integris Allura BH5000; Philips Medical Systems) was used in cooperation with Tsukuba University Hospital to photograph cervical vertebral motions. The photographic device could record 60 frames per second, enabling the system to take cervical vertebral images with 16.67 ms intervals (see Figure 2 (a)). The dose of exposure was 0.016 mGy per frame and the total number of frames for one test was around 15-20. The resolution of the X-ray system is 640 x 512 pixels. The cervical vertebral motions were analyzed by digitizing coordinates for representative points of the cervical vertebrae found in the X-ray images. Also, polynominal approximation of formulation was applied to the smoothing technique for digitizing data of the cervical vertebral motions.

EXPERIMENTAL CONDITIONS: Four normal healthy males and 2 normal healthy females were selected as test subjects. The ages and physical data of the subjects are shown in Table 1. In order to examine the effect of muscle actions on cervical vertebral motions, the experiments were done under two types of conditions: a relaxed state, in which the volunteers

Table 1. Subjects

	ID	Age	Sex	Height [cm]	Weight [kg]
1	I	23	F	164	50
2	II	23	F	162	46
3	III	23	M	176	67
4	IV	25	M	166	61
5	V	25	M	171	57
6	VI	24	M	178	67



(a) Images of cervical vertebrae by cineradiography **(b) Template of cervical vertebrae**

Figure 2. Digitizing method of cervical vertebrae by cineradiography

were subjected to impact in a state of relaxed muscles, and a tense state, in which volunteers intentionally tensed up their muscles.

PHYSIOLOGICAL MOTIONS: To understand the characteristics of cervical vertebral motions at the time of impact, the subjects were asked to make head and neck motions that resembled apparent visual motions during a collision. The cervical vertebral motions at such time were defined as the physiological motion.

INFORMED CONSENT FOR VOLUNTEERS: An informed consent procedure in accordance with the Helsinki Declaration was conducted for all the volunteers. This procedure informed them fully of the purpose and method of the experiment as well as the potential risks in order to obtain their full consent. The details and contents of the experiment were subjected to the approval of the Special Ethics Committee of Tsukuba University Hospital.

METHOD OF ANALYSIS

ANALYSIS OF MOTIONS OF INTERVERTEBRAL DISC AND FACET JOINTS USING X-RAY IMAGES:

Definition of Representative Points of Cervical Vertebrae, Intervertebral Discs and Edges of Facet Joints**:** As shown in Figure 2 (b), cervical vertebral templates were prepared for individual subjects according to the vertebral images obtained from the cineradiography. By fitting each template over the image concerned, the trajectories of cervical vertebral motion was obtained. Edges and segmental coordinates of intervertebral discs and facet joints shown on Figure 3 were defined from the

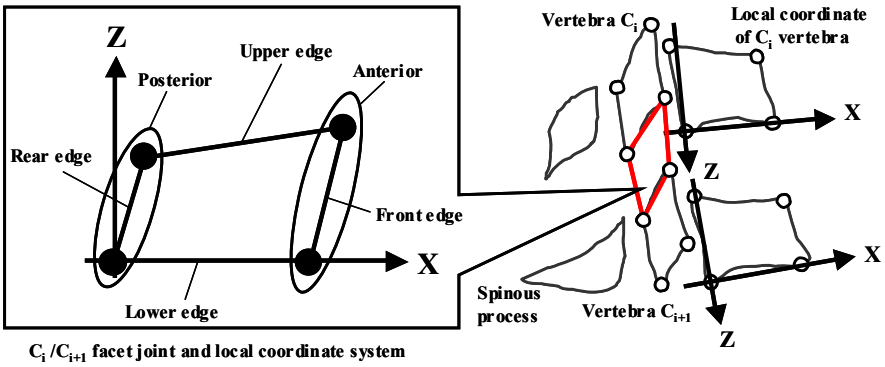


Figure 3. Representative points and local coordinate system of cervical vertebra

representative points shown on the templates of occipital condyle and vertebrae. The physical quantities of intervertebral discs and facet joints were calculated based on the time history of coordinates of the representative points. The analysis error for the digitized process for an X-ray image was defined by the average value and the standard deviation of the ten image readings for one subject.

Physical Quantities Representing Intervertebral Motions: The rotational angle of each intervertebral disc relative to the segmental coordinate system of the seventh cervical vertebra (C7) is necessary in to calculate the rotational angle relative to C7. The rotational angle of the upper intervertebral disc relative to that of the lower intervertebral disc in the segmental coordinate system was analyzed. Using such rotational angles, the relative rotational motions among individual intervertebral discs were also analyzed. The lower edge mid-point (X and Z components) of the upper intervertebral disc in the segmental coordinates of the lower intervertebral disc were normalized by the distances of lower edge front point and rear point of the lower intervertebral disc at the beginning of impact (0 ms). Both horizontal and vertical displacements relative to the lower intervertebral disc were calculated. The segmental motions of the intervertebral discs were analyzed according to the displacements. In each case, positive values represent the quantities of extension and forward displacement, while the negative values represent the quantities of flexion and rearward displacement. The displacement and strain of C6 relative to C7 was not analyzed due to the vague photographic image of partial segment C7.

Physical Quantities Representing Facet Joint Motions: Strains and shear strains of front and rear edges were calculated as physical quantities of facet joint motions. Since strains of the capsular facet joints capsule cannot be directly measured, strains and shear strains of the front and rear edges, which are defined as representative points of the articular process, were used as travel distances of facet joints. As shown in Figure 4, deformation of facet joint capsule grew larger and tension strains in capsular ligaments increased, when rear shear strain and extensive strains occurred in the front and rear edges of the facet joints. A similar phenomenon was observed when front shear strain and compressive strain occur in facet joints. Thus, deformation of facet joint capsule was expressed by strain and shear strain of the front and rear edges of the facet joints. The calculated strain values were used to study the possibility of cervical injuries which occur mainly in soft tissues such as facet joint capsules, intervertebral discs, and ligaments.

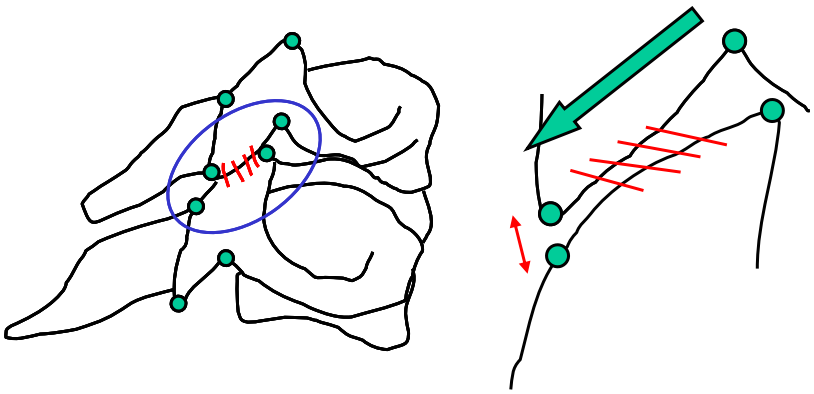


Figure 4. Strains and shear strains of the front and rear edges of facet joints and facet joint capsules

ANALYSIS OF IMPACT FORCE APPLIED TO HEAD AND NECK: Assuming the head as a rigid object, the X-axis was set parallel to a Frankfurt line which is on the origin of the head X-Z plane and an anatomical center of gravity located 5 mm in the forward direction from the auditory meatus and 20 mm on the vertical line of the Frankfurt line. From the tri-axial accelerometer and the tri-axial angular velocity meter attached to the mouth via a mouthpiece, we calculated the linear and rotational

accelerations of the head's center of gravity in the reference coordinate system, and the forces that were acting on the upper neck.

MEASURING THE ACCELERATION OF THE TORSO: To obtain the acceleration of the subjects' upper torso, a tri-axial accelerometer was attached to the skin surface of the T1 (the 1st thoracic vertebra) spinous process, and the acceleration of T1 was measured.

RESULTS

Despite the fact that no occurrence of hyperextension has been recorded since headrests were made mandatory equipment, injuries to the neck still occur. It appears that neck injuries occur when the neck is deformed into an S-shape during the initial stage of the impact. In addition, Prasad et al. (2004) reported that in their experiment with cadavers, the head impacted the headrest at 105-120 ms. In the present research, an effort was made to analyze the impact during the initial phase (up to 120 ms) of the collision by comparing dynamic motions, and considering the effects of muscle tension and gender differences. The peak acceleration of the sled was 42.3 m/s^2 with 110 ms of duration time, and the delta V was 6 km/h.

DIFFERENCES IN CERVICAL VERTEBRAL MOTIONS BETWEEN IMPACT AND PHYSICAL CONDITIONS: Distinguishing differences of motions between impact and physical conditions were the relative stretch of the lower cervical spine (C5/C6 and C6/C7) and rearward displacement. During the initial phase of impact, the upward motion of the torso causes the axial force of compression to act on the neck. Because the intervertebral disc receives such axial compression, stiffness in the shear direction decreases, and the range of motion on the intervertebral disc increases in the shear direction.

Regarding the motion of the facet joints, the angle of the facet joints increases toward the lower cervical spine; furthermore, it appears that when axial compression is at work, the lower cervical vertebrae are more easily moved compared to other vertebrae.

Under such conditions, the shear force from T1 forward acted on the neck, and its impact was transmitted to the lower cervical spine, so there was more displacement of vertebrae and accompanying stretch motion in the lower cervical spine. Such stretch of the lower cervical spine caused shear strain to occur in the front and rear edges of the facet joints and rear edges of intervertebral disc in the C5/C6 and C6/C7 segments.

INFLUENCE OF MUSCLE TENSION: Figures 5 and 6 show the mean values of all subjects in terms of head rotational angle and head horizontal displacement relative to C7 in tensed/relaxed conditions of muscle together with corridors. The corridors were determined by the average value +/- one standard deviation (SD). The positive values are those of the extension and forward displacement relative to C7, while the negative values are those of the flexion and rearward displacement. In both

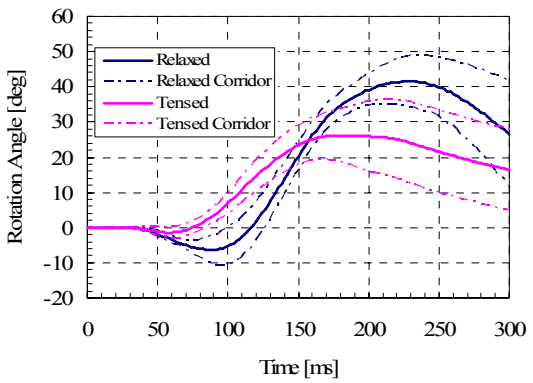


Figure 5. Head rotational angle relative to C7 in tensed/relaxed muscle conditions

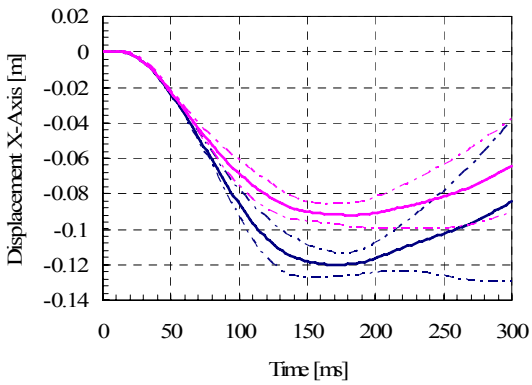


Figure 6. Head horizontal displacement relative to C7 in tensed/relaxed muscle conditions

tensed and relaxed muscle conditions, the head showed extension and rearward displacement relative to C7. The head extension and displacement were reduced from 60% to 80% by the muscle tension when compared to the values in relaxed condition.

EFFECT OF MUSCLE TENSION ON CERVICAL VERTEBRAL MOTION: In a relaxed condition, cervical vertebral motion could be characterized as exhibiting patterns of compression strain in the rear edge of facet joint of the lower cervical spine area of C4/C5 to C6/C7, and rearward shear strain of the upper edge of facet joint, differing with normal physical conditions. Moreover, the motion patterns of the lower cervical spine were much more noticeable in tensed condition than in relaxed condition.

Table 2 shows the maximum values of tensed/relaxed conditions in the cervical vertebra where the maximum compression strain occurred in relaxed condition and the ratios for relaxed condition to tensed condition. The maximum value for the relaxed/tensed ratio of the cervical vertebra where maximum rearward shear strain occurred in relaxed condition, and the ratio for relaxed to tensed conditions are shown in Table 3. In nearly all of the subjects, compression strain of the rear edge of the facet joints, and rearward shear strain of the upper edge of the facet joints, increased by 15% to 80% as a result of this muscle tension.

Table 2. Values of tensed/relaxed conditions in the cervical vertebra where the maximum compression strain occurred in the relaxed condition and the ratios of relaxed and tensed condition

		Compressive Strain		Tensed/Relaxed
	Segment	Relaxed	Tensed	[%]
I	C4/C5	-0.40 (±0.07)	-0.38 (±0.07)	95.3
II	C6/C7	-0.66 (±0.12)	-0.76 (±0.14)	115.7
III	C4/C5	-0.29 (±0.05)	-0.43 (±0.08)	148.5
IV	C6/C7	-0.25 (±0.05)	-0.47 (±0.09)	187.2
V	C6/C7	-0.30 (±0.06)	-0.42 (±0.08)	138.4
VI	C6/C7	-0.40 (±0.07)	-0.06 (±0.01)	14.2

The values in the parenthesis show the standard deviation for the average values.

Table 3. Values of tensed/relaxed conditions in the cervical vertebra where the maximum rearward shear strain occurred in the relaxed condition and the ratios of relaxed and tensed condition

		Shear Strain		Tensed/Relaxed
	Segment	Relaxed	Tensed	[%]
I	C4/C5	0.47 (±0.17)	0.33 (±0.12)	71.2
II	C6/C7	0.72 (±0.26)	0.95 (±0.34)	131.6
III	C4/C5	0.91 (±0.33)	1.31 (±0.47)	144.6
IV	C5/C6	0.46 (±0.17)	0.18 (±0.07)	39.9
V	C6/C7	0.80 (±0.29)	1.34 (±0.48)	168.4
VI	C5/C6	0.51 (±0.18)	0.62 (±0.22)	121.9

The values in the parenthesis show the standard deviation for the average values.

GENDER DIFFERENCES IN NECK FORCES: In the initial stage of impact, female subjects exhibited a greater T1 horizontal acceleration than male subjects (Fig. 7). This T1 horizontal acceleration acted on the lower neck as shear force that extended the head and neck. In addition, the mass of the head of the females were less than that of the males. Furthermore, female cervical spines tend to be smaller and female inertial moment for the neck and head together was smaller. These factors resulted in the rapid increase in head rotational acceleration in the extension (Fig. 8). For female subjects who had a rapid increase of the head rotational acceleration, the bending moment acted on the upper neck during the early stage of impact (Fig. 9). Figures 7, 8, and 9 show the mean values of all subjects in terms of T1 horizontal acceleration, head rotational acceleration, and neck

bending moment.

Looking at local cervical vertebral motion, we found that the bending moment acting on the upper cervical spine began at the initial stage of impact, and the lower cervical spine caused the occurrence of a large forward shear force. As a result, the cervical vertebral rotation angle of female subjects was greater than that of the male subjects, and their cervical spine exhibited a more significant S-shaped deformation (Fig. 10).

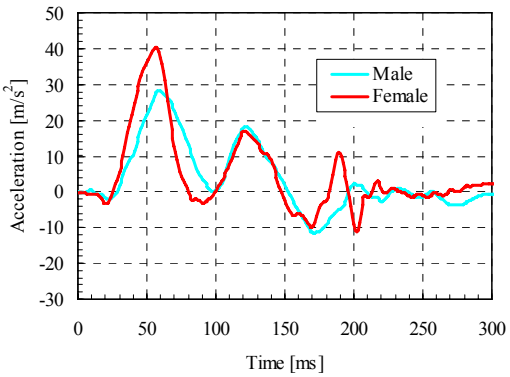


Figure 7. Comparison of T1 horizontal acceleration between male and female

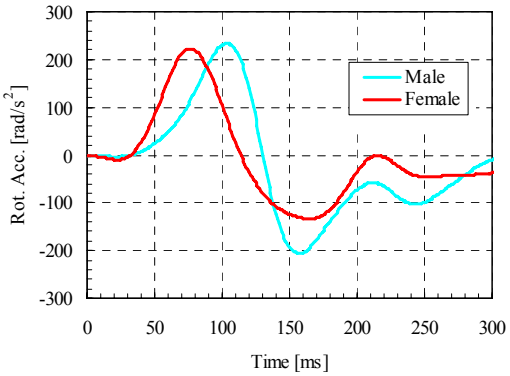


Figure 8. Comparison of head rotational acceleration between male and female

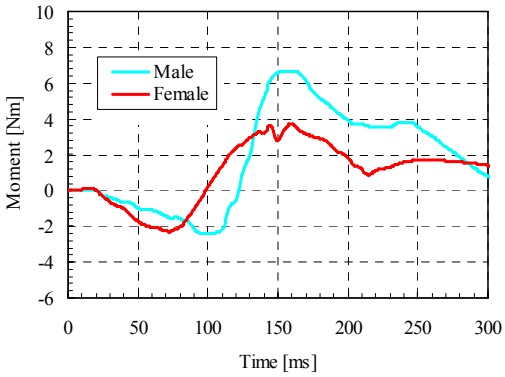


Figure 9. Comparison of bending moment acting on the upper neck between male and female

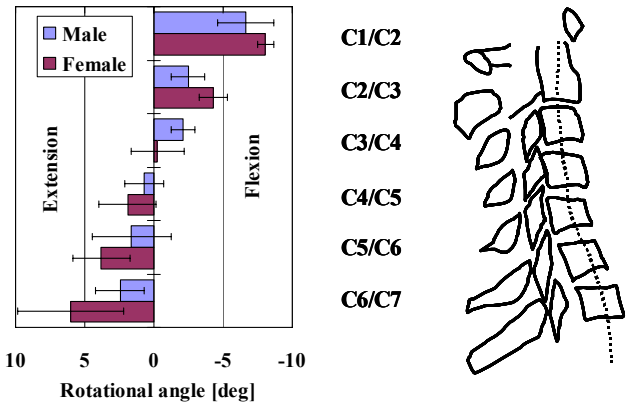


Figure 10. Comparison of cervical vertebral rotational angles between male and female

The difference between male and female was statistically significant as confirmed by t-test ($P \leq 0.05$).

DEDUCING THE MECHANISM OF NECK INJURY OCCURRENCE: There were large compression strain and shear strain in the front and rear edges of the facet joints at C5/C6 and C6/C7. These strains strongly indicate that there was considerable deformation in the joint capsules. In fact, it could have caused damage to the soft tissues around the facet joints, inflammation, and/or recurring pain. The mechanism of neck injury occurrence that can be estimated from the cervical vertebral motion can be summarized as follows:

(1) Axial compression to the intervertebral disc reduced stiffness in the shear direction and increased the range of motion of the cervical vertebrae.
(2) The facet joint angle on the horizontal plane increased toward the lower cervical vertebrae, and when there was compression force at work, the range of motion of the lower cervical vertebra was larger.
(3) Forward shear force was acting on T1 toward the neck; the shear force was transmitted from the lower cervical vertebrae, causing greater extension and backward displacement to the lower cervical vertebrae than during normal physical conditions.
(4) More compression strain of front and rear edges, as well as shear strain occurred in the C5/C6 and C6/C7 facet joints, but it was not observed during physical conditions.
(5) The cervical vertebral motion reported above also caused deformation of the capsular. This in turn could result in damage to soft tissues surrounding facet joint, inflammation, and/or recurring pain.

EFFECTS OF MUSCLE TENSION ON SUPPRESSING THE OCCURRENCE OF NECK INJURY: Even if muscle tension suppressed apparent visual motions, it is clear that there were no suppression effects on local cervical vertebral motions, especially in the lower cervical vertebrae at the time of rear-end impact. On the contrary, muscle tension actually tended to encourage extension and backward displacement between the vertebral bodies, as well as compression strain and rearward shear strain in the facet joints. Even if such apparent visual motions were suppressed, this would not necessarily mean that local cervical vertebral motions were also suppressed. This is one of the important points in understanding the mechanism of neck injury occurrence. It is also important that the methodology to analyze the cervical vertebral motion in the present research be able to provide a thorough understanding of distinguishing cervical vertebral motion that cannot be observed visually.

GENDER-BASED DIFFERENCES IN RISK OF NECK INJURY OCCURRENCE: In the facet joints of the lower cervical spine, female subjects experienced greater compression strain of the front and rear edges, and greater shear strain than male subjects, indicating that females are at a higher risk of suffering neck injury.

Statistical analyses of the degree of Cervical Spine Disorder (CSD) by Hell et al. (2003) resulting from accidents that happened in Germany in 2000 indicated that females were more at risk of sustaining CSD than males. Brault et al. (1998) conducted a simulated rear-end impact experiment, and reported that females were more likely to suffer long-term symptoms than males. Stemper et al. (2003) reproduced whiplash motions using just the head/neck complex of cadavers to compare cervical vertebral motions of males and females. They reported that females had a larger rotation angle of the cervical vertebrae than males, and that females were more susceptible to neck injury than males. In the same way, results obtained from the present experiment agree with previous statistical accident data and clinical information.

THRESHOLD OF NECK INJURY OCCURRENCE BASED ON CERVICAL VERTEBRAL MOTIONS: Despite the fact that visual motions of the head/neck at the time of impact appear to be similar to the head/neck motions under physical conditions, cervical vertebral motions are in fact different. Moreover, although muscle tension helped to suppress apparent visual motions, it did not suppress cervical vertebral motions, which are believed to be the cause of neck injury. From these results, it appears that existing neck injury evaluation indications based on apparent visual motions cannot satisfactorily evaluate localized cervical vertebral motions that are the cause of neck injury occurrence. Thus, it is necessary to evaluate neck injuries based on localized cervical vertebral motions.

Therefore, the present study attempted to investigate the threshold of neck injury occurrence based on localized cervical vertebral motions. However, because none of the volunteers in the experiment

actually experienced neck injury, it was impossible to investigate the threshold for actual neck injury occurrence. Therefore, the experiments were conducted not as an indicator of actual neck injury, but rather as an indicator of the presence or absence of some sense of discomfort. The corresponding relationship between front/rear strains and shear strain of the facet joints for each subject was analyzed to investigate the threshold of neck injury occurrence.

Table 4 shows the symptoms of the test subjects after the experiment. Subjects III, IV and VI complained of discomfort such as neck pain. This "discomfort in the neck" manifested itself in 3 of the 6 subjects as light stiffness, etc. in the neck. But within 3 days, all symptoms in all 3 subjects disappeared.

Figure 11 shows plots at 10 ms intervals of front edge strain and shear strain in the C2/C3 to C6/C7 facet joints of all subjects, while Figure 12 shows plots with the same conditions but for rear edge strain and shear strain. Higher strain occurred in subjects III and IV, who complained of neck discomfort after the experiment. These strain values, indicated by the broken lines in Figures 11 and 12 were used to estimate the thresholds for each type of strain in facet joints in Table 5. Using these estimated threshold values, subjects were classified into neck pain and no neck pain groups, which could be used to distinguish between the zones by the broken lines added to Figures 11 and 12. This suggests that strain of facet joints can be used to evaluate the occurrence of neck injury.

Table 4. Symptoms of test subjects after the experiment

ID	Symptoms after experiments
I	No Symptom
II	No Symptom
III	Cervical muscular pain for 2 days
IV	Shoulder discomfort for 2 days
V	No Symptom
VI	Shoulder muscular pain only on that

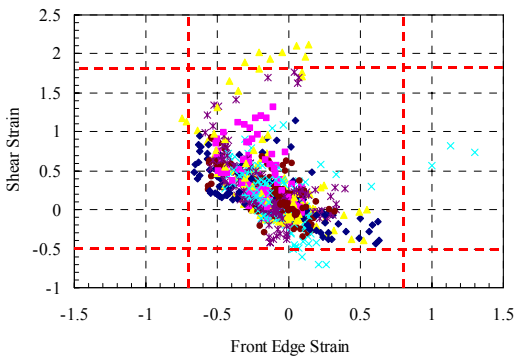


Figure 11. Plots at 10 ms intervals of front edges strain and shear strain in the C2/C3 to C6/C7 facet joints of all subjects

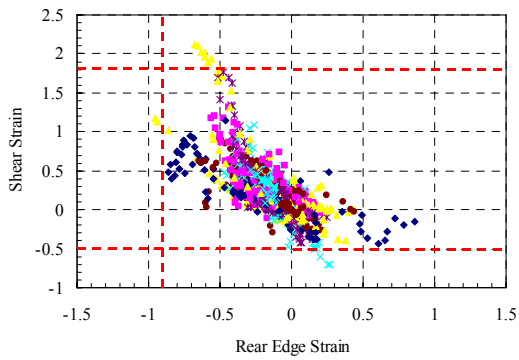


Figure 12. Plots at 10 ms intervals of rear edges strain and shear strain in the C2/C3 to C6/C7 facet joints of all subjects

Table 5. Estimation of the thresholds for each type of strain in the facet joint

	Front edge strain		Rear edge strain		Shear strain	
	Tension	Compression	Tension	Compression	Posterior	Anterior
Threshold	0.8	-0.7	-	-0.9	1.8	-0.5

LIMITATION OF THIS STUDY: The set of experimental data was insufficient to make a generalization based on the results because the subjects were limited to only six volunteers. Moreover since the force that was applied to simulate the impact that causes neck injury was minimized for the safety of the subjects, the results of this research cannot be extrapolated to neck injuries where the level of impact is higher than what was applied in the study. Therefore, in future studies it will be necessary to investigate the threshold of neck injury occurrence at high impact levels by conducting neck motion analyses using suitable extrapolation methods for human volunteer tests, with simulations that more closely approximate living beings.

CONCLUSIONS

Six human volunteers (4 males, 2 females) were subjected to low-impact level rear-end collision experiments. Quantitative analysis using strain on cervical vertebral motions in relaxed and tensed conditions provided the following results:

- A comparison of cervical vertebral motion during impact and physical conditions showed that during impact there was shear strain in the facet joints at C6/C7 and C5/C6 and compression strain of front/rear edges, suggesting that neck injury could occur in this area.
- By comparing the head/neck and cervical vertebral motions under relaxed and tensed muscle conditions, we found that the cervical vertebral motions could not be suppressed by muscle tension, despite the fact that head/neck motions were markedly suppressed.
- A comparison of the cervical vertebral motions of male and female subjects revealed that females were subjected to higher shear strain and compression strain of the front/rear edges of facet joints. Thus, females had a higher risk of sustaining neck injury. This finding agrees with other statistical accident data and clinical information.
- An investigation was made of the possibility of neck injury occurrence from the correlation between shear strain and front/rear edge strain of the facet joints, and the symptoms of the volunteers after the experiment. This correlation indicated that a threshold could be set at which deformation of joint capsules, etc. surrounding the spine and facet joints could lead to the occurrence of injury.

ACKNOWLEDGEMENT

We would like to express our appreciation to the Toyota Motor Company, for funding the present research.

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