INFLUENCES OF NECK MUSCLE TENSION ON CERVICAL VERTEBRAL MOTIONS DURING DIRECT LOADING ON HUMAN HEAD

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ABSTRACT

Direct impact loading experiments on human volunteer's head were conducted at low impact force levels in frontal collisions simulating impact pattern of airbag deployments, for quantitative analysis on segmental motions of intervertebral disc and facet joints during impact.

Under forehead rearward impact, the head extension relative to the torso was reduced by neck muscle tension. However, the local motion of C5 relative to C6 that was large under the relaxed condition of neck muscles was not reduced. Further, the compressive strains of rear edge of the C5/C6 intervertebral disc and the C5/C6 facet joint were increased. Under chin rearward impact, the head flexion relative to the torso and C7 during neck S-shape curve was reduced by neck muscle tension. The flexion of C1~C3 relative to each lower vertebra, which was large under the relaxed neck muscles condition, were reduced too. However, the inflection point of cervical spine S-shape curve between C3 and C4 occurred when the relative flexion between C3 and C4 was reduced to less than that of C1 and C2. Moreover, there was no reduction effect on the tensile strain of rear edge of the C3/C4 facet joint.

The kinematics of the head and neck was reduced by neck muscle tension during low-severity impact. On the contrary, the influence of neck muscle tension on the intervertebral motion was negligible. The study indicated that such local motion could not be sufficiently evaluated by existing neck injury criteria that are calculated from the kinematics of the head and neck. Thus, it is imperative to clarify the mechanism of minor neck injuries based on intervertebral motion for the investigation of minor neck injury criteria.

KEY WORDS: INJURY CRITERIA, MUSCLE, NECK, VOLUNTEERS, and WHIPLASH

NECK INJURIES CAUSED BY automobile accidents are generally minor injuries, but pose a serious social issue in terms of the amount of accident damage compensation. Therefore, clarification of the minor neck injury mechanism is an urgent issue to be dealt with quickly. Since minor neck injuries generally occur in rear-end collisions, efforts to clarify the injury mechanism have been mainly focused on the rear-end collisions. Based on the result of clinical studies, however, it is deduced that many nerve and soft tissues distributed around a facet joint capsule are apt to be damaged and result in a chronic neck injury (Siegmund et al., 2001). It is reported that the damage of soft tissues of facet joint and rupture of the facet capsule were found also in cadaver tests simulating whiplash (Yoganandan et al., 2001; Cusick et al., 2001). Adam et al. (2004) noted the extreme compression of facet joints and the facet capsule ligaments, and reported on the relationship between the facet joint motions and the incidence of neck injuries according to the cadaver experiments simulating whiplash motion. The frequent occurrence of neck injuries found also in frontal impacts has been studied as a serious issue in recent years (Roselt et al., 2002; Kullgren et al., 2000a, 2000b), but a clear determination of the mechanism has not been achieved. Such neck injuries generally occur at relatively low impact force levels in both rear and frontal collisions (Jakobsson et al., 2000; Olsson et al., 1990). It is thus deduced that the influence of occupant muscle tension is significant on the occupant head and neck motions as well as on the neck injuries caused by the motions. Adames et al. (1998) deduced that the compression force and the moment on the neck increased with the tension of neck muscle, which facilitated the occurrence of neck injury. However, the influence of occupant muscle tension on the occurrence of neck injury at low impact force levels has not been clearly determined. In such regards, the authors et al. decided to conduct direct impact loading experiments on human volunteer's head using low impact force levels based on the impact pattern of airbag deployments upon frontal collision, and to clarify the influence of subject's muscle tension on the head/neck motions during impact. It was also decided to conduct quantitative analysis of the segmental motions of intervertebral disc and facet joint. This was done to clarify the influence of muscle tension on the cervical vertebral motions in line with the influence on the local motions. According to the relationship between the cervical vertebral motions and the occurrence possibilities of neck injuries, efforts have been made under this study to clearly determine minor neck injury incidence and the factors that are deemed necessary for such evaluations.

EXPERIMENTAL METHODS

HEAD IMPACT LOADING SIMULATING AIRBAG IMPACT : This study conducts experiments on human volunteers simulating the head impact patterns of airbag deployments in frontal collisions. Figure 1 shows the schematic of the impact loading device. First, a subject was seated on a rigid seat with the seatback installed. Then a 3kg weight was dropped freely from the 0.4 m height onto the wire wound around the forehead or chin of the subject to apply a low impact force level on the head.

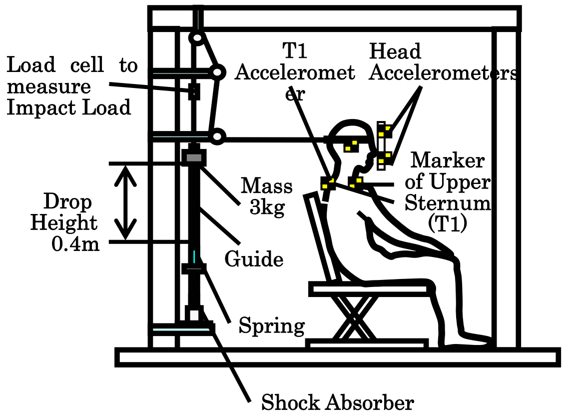


Fig.1 Experimental apparatus

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

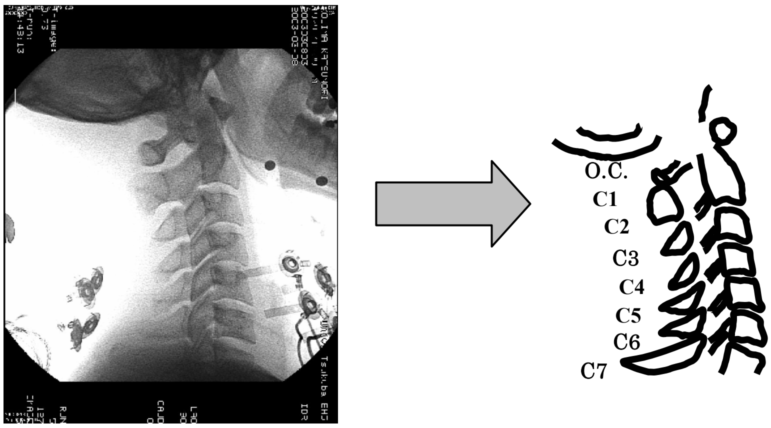
PHOTOGRAPHY OF CERVICAL VERTEBRAL MOTIONS USING CINERADIOGRAPY: For the analysis of cervical vertebral motions during impacts, a cineradiographic system (Philips: BH500) was used with Tsukuba University Hospital to photograph cervical vertebral motions. The system was capable of taking cervical vertebral images as shown in Figure 2 (a) with 16.67 ms intervals, owing to the photographic device with the performance of taking 60 frames per second and the dose of exposure was 0.016 mG per frame. The total number of frames for one test is around 15-20. The cervical vertebral motions were analyzed by digitizing coordinates for the representative points of cervical vertebrae found in the X-ray images. And also, the polynominal approximation of formulation was applied for smoothing technique on the digitizing data of the cervical vertebral motions.

Table 1 Subjects

Subject ID	Sex	Age	Height [cm]	Sitting Height[cm]	Weight [kg]
I	M	38	172	92	75
II	M	22	173	91	70
III	M	23	171	89	65
IV	M	22	174	92	70
V	M	21	177	91	75
VI	M	20	172	89	60

CONDITIONS OF EXPERIMENTS: Six healthy male adult volunteers were selected as the test subjects. The age and physical structural data of each subject are shown in Table 1. Three regions and directions of impact loading were selected assuming three impact directions of airbag deployments - namely, forehead rearward impact, chin rearward impact and the chin upward impact. Two different test conditions were set to find the influence of muscular conditions on the cervical vertebral motions at each impact loading location. That is, the state with the subject's neck relaxed (non-tense state) and the state with the neck stiffened by the will of the subject (tense state). In this paper, only the forehead rearward impact and chin rearward impact tests assuming full-face impact condition will be reported.

INFORMED CONSENT FOR VOLUNTEERS: The informed consent procedure in line with the Helsinki Declaration was conducted for all the volunteers. This procedure informs them fully of the purpose and method of experiments as well as the potential risks, thereby ensuring their full consent. The details/contents of the experiments were subjected to the approval of Special Committee of Ethics, Medical Department, Tsukuba University.



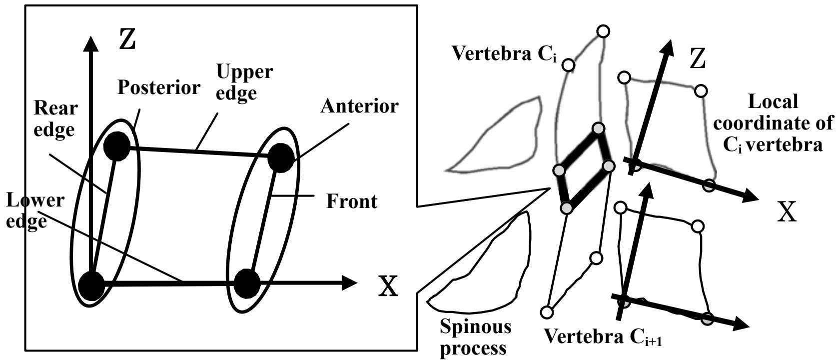
(a) Images of cervical vertebrae by cineradiography **(b) Template of cervical vertebrae**

Fig.2 Digitizing method of cervical vertebrae by cineradiography

ANALYTICAL METHODS

METHOD OF ANALYSIS ON MOTIONS OF INTERVERTEBRAL DISC & 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 cervical vertebral motion was digitized. Edges and segmental coordinates of intervertebral discs and facet joints were defined as shown in Figure 3 from the representative points shown on the templates of occipital condyle and vertebrae. According to the time history of coordinates of the representative points, the physical quantities of intervertebral discs and facet joints were calculated.

Physical Quantities Representing Intervertebral Motions: The rotational angle of each intervertebral disc relative to the segmental coordinate system of the seventh cervical vertebra (C7) was necessary in calculating the rotational angle relative to C7. The rotational angle of upper intervertebral disc relative to those of the lower intervertebral disc in the segmental coordinate system was analyzed. Using such rotational angles, the relative rotational motions among individual intervertebral disc were also analyzed. The quantities of lower edge mid-point travels (X and Z components) of the upper intervertebral disc in the segmental coordinates of lower intervertebral disc were normalized by the distances of lower edge front point and rear point of the lower intervertebral



C_i /C_{i+1} facet joint and local coordinate system

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

disc at the beginning of impact (0 ms) and calculated as the horizontal and vertical displacements relative to the lower intervertebral disc. The segmental motions of the intervertebral discs were analyzed according to the displacements. In each case, the positive values represent the quantities of extension and forward displacement, while negative values represent the quantities of flexion and rearward displacement. The displacement and strain of C6 relative to C7 could not be analyzed due to the vague photographic image of partial segment C7.

Physical Quantities Representing Facet Joint Motions: Strains of front and rear edges were calculated as physical quantities of facet joint motions. The calculated strains were used for the study on the possibility of occurrence of cervical injuries caused by impingement of synovial folds caught by extreme compression of front/rear edge of facet joint or by rupture of the facet capsule due to an extreme tensile load.

Measurement Errors in Physical Quantities Representing Motions of Intervertebral Disc & Facet Joint: A series of analysis has been done and conducted 10 times with the following procedure. For the X-ray images taken on each subject, corresponding templates were fit over the images then proceed to the formation of coordinates. The calculated standard deviations of the physical quantities representing the motions of intervertebral discs and facet joints were considered as the measurement errors. The measurement error of each physical quantity was 0.47 deg for the intervertebral disc rotational angle, 0.28 mm for the horizontal displacement, and 0.04 for the front/rear edge strain of facet joint.

METHOD OF ANALYSIS ON MUSCLE RESPONSES USING ELECTROMYOGRAPHY: The responses of sternoclaidmastoid muscles (SCM) and paravertebral muscles (PVM) were measured, in order to find out how and to what extent any cervical muscle actually reacts to an impact. By rectifying and smoothing the measured electromyographic amplitude values, it became possible to calculate each average rectified value (ARV) – an indication for the evaluation of cervical muscle response. Then the ARV in the subject's muscle in each experiment was normalized to the maximum value of corresponding ARV in a non-tense state of the subject. Using ARVs obtained from the above, the intensity of cervical muscle activities in non-tense state and tense state of neck upon impact was monitored.

METHOD OF ANALYSIS ON IMPACT FORCES APPLIED TO HEAD AND NECK: For the calculation of linear and rotational acceleration at the head center of gravity, four single axis accelerometers were attached to the head of each subject. Assuming that the head was rigid and the motions were two-dimensional, the original point of reference coordinates of head X-Z plane was set at a location 5 mm in forward direction from the auditory meatus located on the Frankfurt line, and at the anatomical center of gravity located 20 mm above the auditory meatus on the vertical line. The X-axis was set in parallel to the Frankfurt line. The 4-channel acceleration measurement method (Ono et al., 2001) was applied and the linear and rotational acceleration at the head center of gravity was calculated according to the coordinates of individual accelerometers and the measured values.

MEASUREMENT OF TORSO (FIRST THORACIC VERTEBRA: T1) ACCELERATION : A three-axial accelerometer was adhered over the skin surface of T1 spinous process for the measurement of T1 acceleration.

CALCULATIONS OF PRESENT EVALUATION INDICES FOR NECK INJURY: In this study, it was decided to examine the influences of muscle tension on the cervical vertebral motions and values of present neck injury evaluation indices. According to Ono et al. (2002), the extension or S-shape deformation of head/neck was found upon impact under the same impact conditions as those in this study. Hence, this study calculated the following two evaluation indices, as they were deemed available to the direct head impact loading condition.

NIC (NECK INJURY CRITERION): It is at present a widely used evaluation index (Bostrom et al., 1996) for the incidence of neck injury in the S-shape deformation. It is also an evaluation index based on the head/neck motions calculated from the head horizontal acceleration and velocity relative to the torso. It is deduced from the results of experiments conducted on pigs that a neck injury would occur where the index value exceeds 15 m^2/s^2 for human being.

IV-NIC (INTERVETEBRAL – NECK INJURY CRITERION): According to the assumption that a neck injury occurs where the cervical vertebral motion exceeds the physiological limit, IV-NIC (Panjabi et al., 1999) is calculated as an evaluation index from the segmental motion of cervical vertebra. It is the maximum value within the physiologically movable limits of cervical vertebral extension and flexion during impact, calculated by dividing the relative rotational angles among the cervical vertebrae concerned. It is presumed that a neck injury occurs where the maximum value of IV-NIC exceeds 1.0 in extension or flexion. It is believed that the IV-NIC is not only indicative of the possibility of neck injury incidence, but also capable of evaluating the region of injury and the cause of injury (extension or flexion). It may be also considered an important index, since the cervical vertebral motions accompanying their relative linear and rotational motion are indirectly showing the distortion of soft tissues surrounding to cervical vertebrae, facet joint, and articular capsule are considered equally important. However, the usefulness of IV-NIC has been verified only in artificial cervical vertebrae, not in real living creatures.

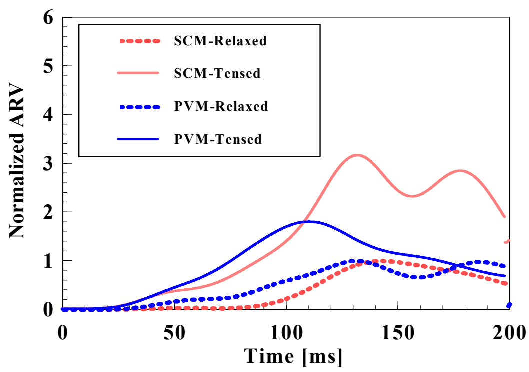
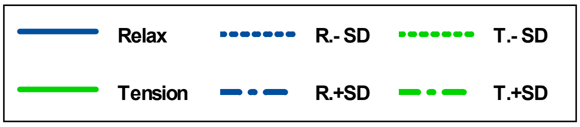


Fig.4 Forehead Rearward Impact: ARV of SCM and PVM (Typical cases)

RESULTS

MUSCLE RESPONSES: The kinematics of the head/ neck and the neck forces of the volunteer in this experiment were almost the same as the tendency that was reported by Ono et al. (2002). Figure 4 shows the ARVs (average rectified values) of SCM (sternoclaidmastoid muscles) and PVM (paravertebral muscles) in relaxed and tense states in typical forehead rearward impacts. At every impact loading condition, the ARV of SCM in tense state tends to become greater than that in relaxed state. A similar tendency is found in the ARV of PVM, but the difference between the relaxed and tense states is not so great as in the case of SCM. All subjects show similar tendencies to each other. The same can be said in forehead rearward impacts. It is thus confirmed that muscle responses become more active in the tense state according to the results of aforementioned experiments.

INFLUENCE OF MUSCLE TENSION ON KINEMATICS: Figures 5 and 6 show the mean values of all subjects in terms of head rotational angle and the horizontal displacement relative to C7 in tense/relaxed states of muscle in forehead rearward impact together with the corridors. The



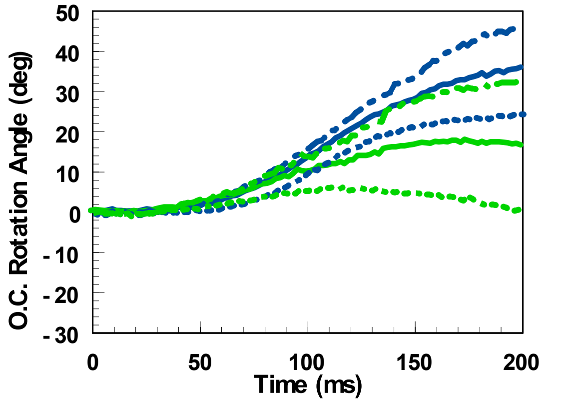


Fig.5 Forehead Rearward Impact : Head rotational Angles relative to C7 (Average +/-SD)

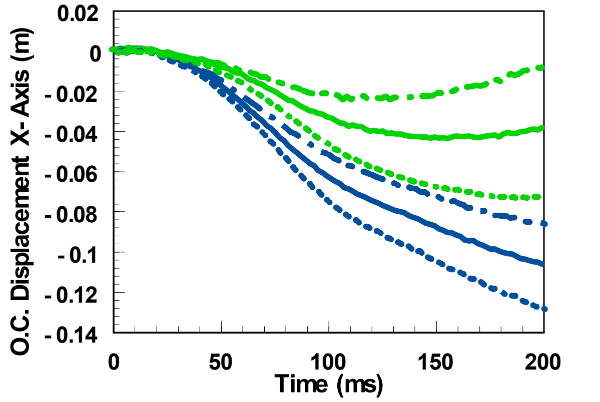
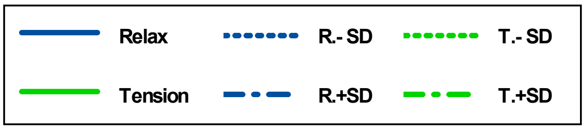


Fig.6 Forehead Rearward Impact : Head horizontal Displacements relative to C7 (Average +/-SD)



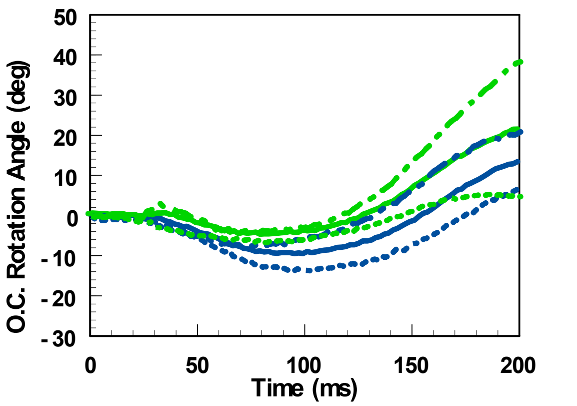


Fig.7 Chin Rearward Impact : Head rotational Angles relative to C7 (Average +/-SD)

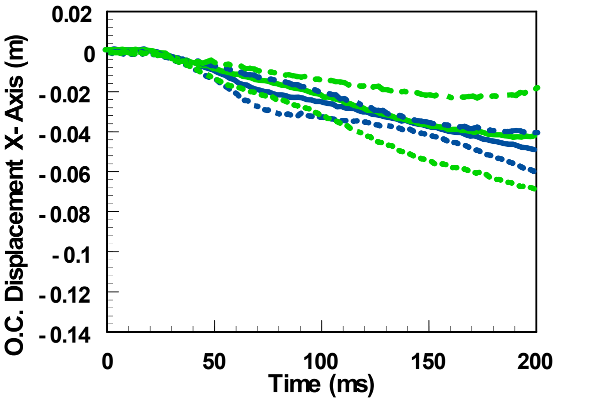


Fig.8 Chin Rearward Impact : Head horizontal Displacements relative to C7 (Average +/-SD)

corridors were determined by the average value +/- one standard deviation (SD). The positive values are those of extension and forward displacement relative to C7, while the negative values are those of flexion and rearward displacement. In both tense and relaxed states of muscle, the head shows the extension and rearward displacement relative to C7. The head extension and rearward displacement in forehead rearward impact are reduced to 40 % or so by the muscle tension in comparison to the values in relaxed state. Figures 7 and 8 show the mean values of all subjects in terms of head rotation angle and the horizontal displacement relative to the torso in tense/relaxed state of muscle in chin rearward impact together with the corridors. In both tense and relaxed states of muscle, the head shows the flexion and rearward displacement relative to C7, and the neck shows the S-shape deformation in the former half of impact - 0 to 100 ms of chin rearward displacement. The head flexion in chin rearward impact is reduced to 50 % or so by the muscle tension in comparison to the flexion in relaxed state.

INFLUENCE OF MUSCLE TENSION ON CERVICAL VERTEBRAL MOTIONS : Cervical Vertebral Motions in Relaxed State : In previous experiments on volunteers conducted by Ono et al. (2002) under similar conditions used in this study, the kinematics - the head rotational angle in particular - were suppressed markedly by the muscle tension at every impact loading condition. Therefore, it might be deduced that extreme local motion among the cervical vertebrae - i.e., motions among intervertebral discs and facet joints may be suppressed greatly by the muscle tension. The influences of muscle tension on impact loading condition in relaxed state found in this study were as summarized below.

Forehead Rearward Impact: Figure 9 shows the rotational angles of intervertebral segments relative to the lower intervertebral segments under relaxed state during forehead rearward impacts. It is found that the extensions of C4/C5 and C5/C6 are greater than those other intervertebral segments.

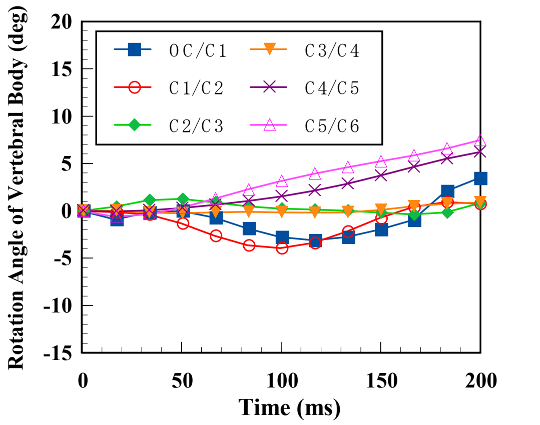


Fig.9 Forehead Rearward Impact : rotational angles of cervical vertebra relative to lower vertebra (Average; Relax)

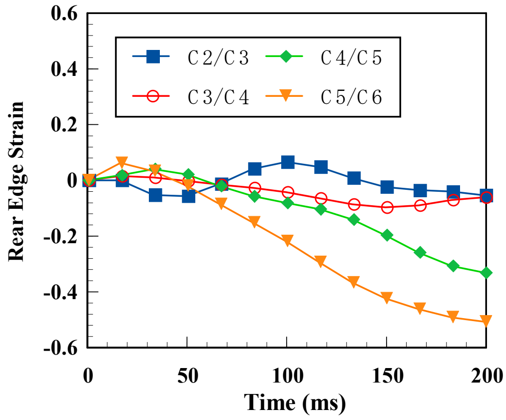


Fig.10 Forehead Rearward Impact : strains of posterior edge of facet joints (Average; Relax)

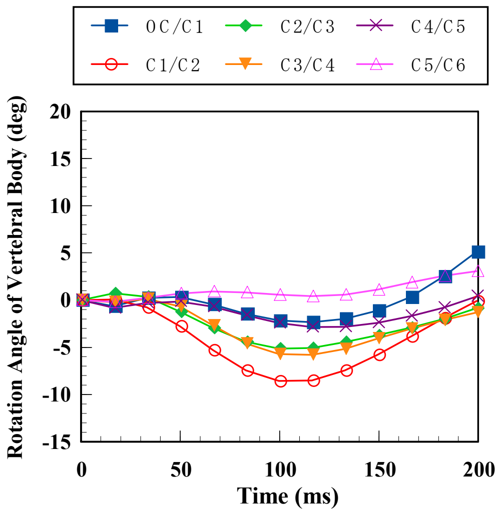


Fig.11 Chin Rearward Impact : rotational angles of cervical vertebrae relative to lower vertebrae (Average; Relax)

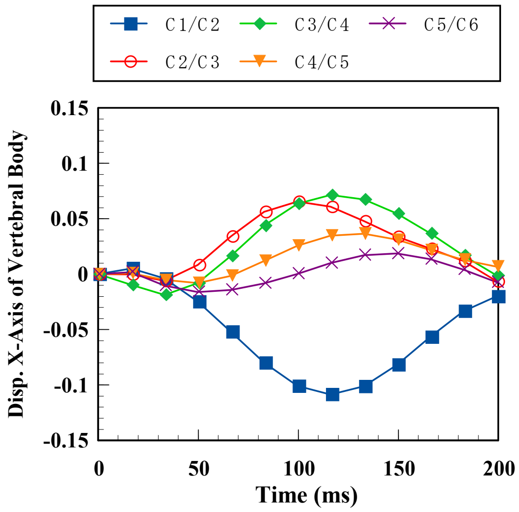


Fig.12 Chin Rearward Impact : horizontal displacements of cervical vertebrae relative to lower cervical vertebrae (Average; Relax)

Figure 10 shows the strains at the rear edge of individual facet joint. It is found that the compression at the rear edge of C5/C6 facet joint is greater than those at the edges of other facet joints.

Chin Rearward Impact: In chin rearward impact, C1 - C3 flex while C4 - C6 extend relative to C7, which results in the S-shape deformation, with the C3/C4 becoming the inflection point of cervical spine. Figures 11 and 12 show the rotation angles and horizontal displacements of individual intervertebral segments relative to the lower intervertebral segments. Relatively greater flexions are found at C1/C2, C2/C3 and C3/C4 (Fig.11), and a relatively greater forward displacement is found at C1/C2 (Fig.12). Figure 13 shows the strains at the rear edges of facet joints. It is found that the tension at the rear edge of C3/C4 facet joint becomes particularly apparent. The motions of intervertebral discs and facet joints reached their peaks around 100 ms in every case.

COMPARISON OF CERVICAL VERTEBRAL MOTIONS BETWEEN MUSCLE TENSE AND RELAXED STATES : With special attention paid to the motions of C5/C6 vertebral segments and the rear edges of facet joint showing particular characteristics of motions of muscle in relaxed state during forehead rearward impacts, and to the motions of C3/C4 vertebral segments and the rear edges of facet joint during chin rearward impacts, the influences of muscle tension on cervical vertebral motions during the period of 0 to 150 ms from the moment of impact with the continuation of impact against the head are discussed in the following.

Table 2 shows the maximum values of the extension angles and the rearward displacements of C5 relative to C6 under the muscle relaxed state during forehead rearward impacts. The extension angle of C5 relative to C6 is not suppressed significantly by the muscle tension, and some subjects even show greater maximum values of extension angle. The rearward displacement of C5 relative to C6, on the other hand, is reduced by the muscle tension. Table 3 shows the maximum values of compressive strains at rear edges of C5/C6 facet joints under forehead rearward impacts in both tense and related states of muscle. In both states of muscle, the compressive strain is increased at the rear edges of C5/C6 facet joints due to the muscle response. Table 4 shows the maximum values of the flexion angle and the rearward displacement of C3 relative to C4, in both muscle relaxed and tense states during chin rearward impacts. The flexion angle and forward displacement tend to increase by the muscle tension - particularly the forward displacement. Table 5 shows the maximum values of tensile strains at the rear edges of C3/C4 facet joints during chin rearward impacts in both tense and related states of muscle. In both states of muscle, the tensile strain at the rear edges of C3/C4 facet joints tends to decrease due to the passive muscle response.

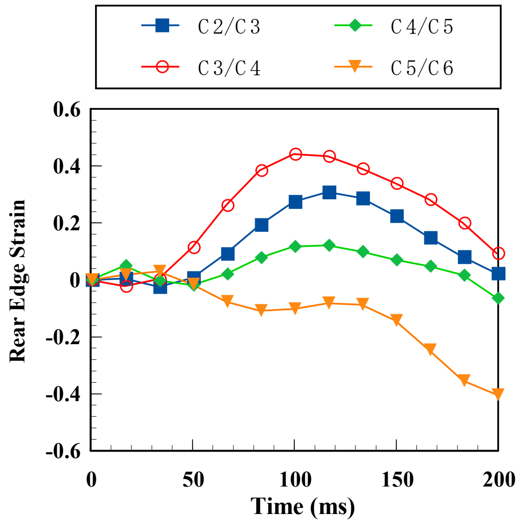


Fig.13 Chin Rearward Impact : strains of posterior edges of facet joints (Average; Relax)

Table 2 Forehead Rearward Impact : maximum extension angles and rearward displacements of C5 relative to C6 for each volunteer

(a) Flexion angles

Subject	Relaxed		Tensed		Tensed/Relaxed
ID	Angle (deg.)	Time (ms)	Angle (deg.)	Time (ms)	(%)
I	4.3	133	3.5	150	81.3
II	6.2	150	5.5	133	89.0
III	5.2	150	7.0	150	135.0
IV	4.1	150	4.5	150	107.9
V	5.0	150	11.0	150	220.1
VI	7.2	150	6.1	150	83.7

(b) Rearward displacements

Subject	Relaxed		Tensed		Tensed/Relaxed
ID	Disp. X-axis	Time (ms)	Disp. X-axis	Time (ms)	(%)
I	0.051	83	0.220	83	43.1
III	0.056	150	0.046	150	82.1
V	0.075	150	0.068	150	90.7
VI	0.128	150	0.030	150	23.4

Table 3 Forehead Rearward Impact : maximum compressive strains at posterior edge of C5/C6 facet joint for each volunteer

Subject	Relaxed		Tensed		Tensed/Relaxed
ID	Strain	Time (ms)	Atrain	Time (ms)	(%)
II	0.39	150	0.48	150	123.1
III	0.43	150	0.49	150	114.0
IV	0.53	150	0.12	116	23.5
V	0.36	150	0.50	150	138.9
VI	0.32	150	0.42	150	131.3

Table 4 Chin Rearward Impact : maximum flexion angles and forward displacements of C3 relative to C4 for each volunteer

(a) Flexion angles

Subject	Relaxed		Tensed		Tensed/Relaxed
ID	Angle (deg.)	Time (ms)	Angle (deg.)	Time (ms)	(%)
I	4.6	116	4.9	150	106.5
II	7.1	133	6.8	116	95.8
III	4.8	116	3.7	116	77.1
IV	8.0	116	7.8	116	97.5
V	5.7	116	4.2	100	73.7

(b) Forward displacements

Subject	Relaxed		Tensed		Tensed/Relaxed
ID	Disp. X-axis	Time (ms)	Disp. X-axis	Time (ms)	(%)
I	0.07	116	0.06	150	85.7
II	0.10	133	0.07	133	70.0
III	0.07	116	0.06	150	85.7
V	0.11	100	0.02	150	18.2
VI	0.03	116	0.00	100	0.0

INFLUENCE OF MUSCLE TENSION ON CONVENTIONAL NECK INJURY CRITERIA: Table 6 shows the NIC maximum values in both relaxed and tense states of muscle during chin rearward impacts where the S-shape deformation occurred. In both states of muscle, the NIC maximum values tend to decrease by the tension of muscle. Figures 14 and 15 show average values of IV-NIC for all volunteers in relaxed/tense muscle states during forehead rearward and chin rearward impacts. The average values and the standard deviations illustrated in Figure 14 and Figure 15 are shown in Table 7 and Table 8. The IV-NIC values of relative extensions of individual intervertebral segments are shown in negative values, while those of relative flexions are shown in positive values. During forehead rearward impacts, the IV-NIC absolute values of C5 extension angle relative to C6 become particularly higher in both relaxed/tense states of muscle with maximum noted at around 150 ms. Those values do not change significantly by the muscle tension. In chin rearward impacts, on the other hand, the IV-NIC absolute values of flexion angles of C2/C3 and C3/C4 become particularly higher in both relaxed/tense states of muscle with maximum observed at around 100 ms. Those values tend to become somewhat smaller by the muscle tension, but the IV-NIC values of C3 relative to C4 do not become significantly smaller. Similar tendencies are found among all volunteer subjects.

Table 5 Chin Rearward Impact : maximum tensile strains at posterior edge of C3/C4 facet joint for each volunteer

Subject	Relaxed		Tensed		Tensed/Relaxed
ID	Strain	Time (ms)	Strain	Time (ms)	(%)
I	0.26	99.6	0.13	116	50.0
II	0.18	132.8	0.10	150	55.6
III	0.17	132.8	0.16	83	94.1
V	0.19	99.6	0.18	83	94.7

Table 6 Maximum values of NIC on Chin Rearward Impacts for each volunteer

Subject	NIC (m^2/s^2)		Tensed/Relaxed
ID	Relaxed	Tensed	(%)
I	0.30	0.28	92.9
II	0.46	0.38	83.5
III	0.42	0.31	75.4
IV	0.34	0.66	193.3
V	0.43	0.42	98.2
VI	0.36	0.31	87.1

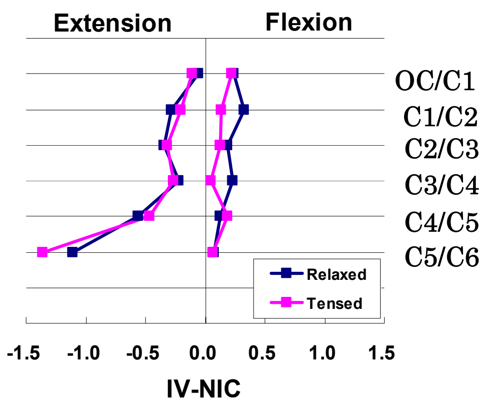


Fig.14 IV-NIC of Forehead Rearward Impacts (All volunteers: Average)

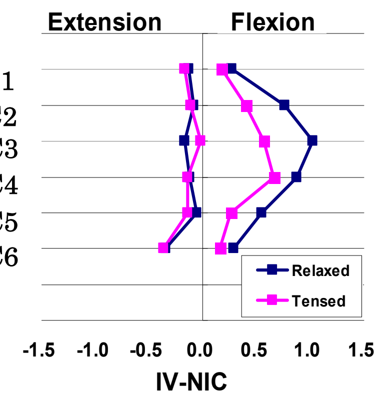


Fig.15 IV-NIC of Chin Rearward Impacts (All volunteers: Average)

Table 7 Average IV-NIC for Forehead Rearward

	Relaxed				Tensed			
	Extension		Flexion		Extension		Flexion	
	Average	+/-S.D.	Average	+/-S.D.	Average	+/-S.D.	Average	+/-S.D.
OC/C1	-0.056	0.038	0.243	0.151	-0.104	0.071	0.222	0.273
C1/C2	-0.282	0.203	0.323	0.195	-0.203	0.201	0.134	0.134
C2/C3	-0.345	0.318	0.187	0.157	-0.315	0.208	0.124	0.205
C3/C4	-0.226	0.135	0.226	0.164	-0.269	0.116	0.046	0.030
C4/C5	-0.561	0.250	0.125	0.107	-0.467	0.278	0.189	0.159
C5/C6	-1.111	0.146	0.076	0.052	-1.363	0.574	0.064	0.036

Table 8 Average IV-NIC for Chin Rearward

	Relaxed				Tensed			
	Extension		Flexion		Extension		Flexion	
	Average	+/-S.D.	Average	+/-S.D.	Average	+/-S.D.	Average	+/-S.D.
OC/C1	-0.128	0.073	0.266	0.165	-0.172	0.171	0.175	0.162
C1/C2	-0.085	0.084	0.761	0.231	-0.113	0.137	0.404	0.176
C2/C3	-0.170	0.172	1.023	0.235	-0.021	0.023	0.572	0.378
C3/C4	-0.119	0.097	0.872	0.247	-0.137	0.103	0.665	0.142
C4/C5	-0.060	0.107	0.545	0.133	-0.140	0.120	0.263	0.186
C5/C6	-0.345	0.243	0.293	0.251	-0.362	0.272	0.161	0.142

DISCUSSION

RELATIONSHIP BETWEEN STRAINS AT FACET JOINT'S FRONT/REAR EDGES AND INCIDENCE OF NECK INJURIES: The compressive strain at the rear edges of C5/C6 facet joints became particularly great during forehead rearward impacts, while the tensile strain at the rear edges of C3/C4 facet joints became particularly great during chin rearward impacts, in comparison to those at other regions. Therefore, it can be deduced that an extreme compression at the rear edges of C5/C6 facet joints during forehead rearward impact may cause a neck injury, and an extreme tensile force at the rear edges of C3/C4 facet joints are probable causes of neck injuries. It was also confirmed in actual vehicle rear-end collisions that damages of soft tissues at facet joints of C4/C5 and C5/C6 were found through a clinical study (Load et al., 1996). It was also reported that damages of soft tissues occurred around C4/C5 and C5/C6 facet joints as the consequences of head/neck motions similar to those of forehead rearward impact, in cadaver experiments simulating rear-end collisions conducted by Yoganandan et al. (2001). It was also reported that an intense head impact in a fall to ground level or traffic accident is an impact pattern similar to that of chin rearward impact, which resulted in a number of non-bone fracture injuries at C3/C4 (Ueta, 1998; Koyanagi et al., 2000; Fukushima et. al., 2003). As discussed so far, the injury criteria using strains at the front/rear edges of facet joints agree very well with the clinical knowledge/findings.

EFFECT OF MUSCLE TENSION ON SUPPRESSION OF INTERVERTEBRAL DISC RELATIVE ROTATION AND HORIZONTAL DISPLACEMENT : As shown in Tables 2 and 4, the relative forward/rearward intervertebral disc displacements tend to be suppressed by the muscle tension in comparison to their relative rotational motions, in both forehead rearward impacts and chin rearward impacts. This is presumably because both the cervical extensor muscle such as PVM and the cervical flexor muscle such as SCM have a function to suppress the relative displacement of intervertebral discs, but only the muscle flexion is effective to suppress the cervical vertebral extension, while only the extensor muscle is effective for the suppression of cervical vertebral flexion.

EFFECT OF MUSCLE TENSION ON SUPPRESSION OF NECK INJURY INCIDENCE: Figure 16 shows the Z-coordinate (reference system for local coordinate of vertebral segment C6) for the IAR (Instantaneous Axis of Rotation) of C5 relative to C6, at the moment when the maximum compression at the rear edges of C5/C6 facet joints occurs, which are shown separately for relaxed and tensed states of muscle. The calculation method of the IAR is discussed in previous studies (Kaneoka and Ono, 1998; Fuss, 1991; Penning, 1988). The IAR tends to move upward with the tension of muscle. In the previous study of the simulated rear-end collision with using volunteers, it was reported that the compression motion at the rear edges of the C5/C6 facet joints was observed by the upward travel of the IAR position of C5 relative to C6. It is deduced that the interaction at the rear edges of C5/C6 facet joints tends to occur easily by the upward travel of IAR resulting in the increase in compression at the rear edges of C5/C6 facet joints in tense state of muscle.

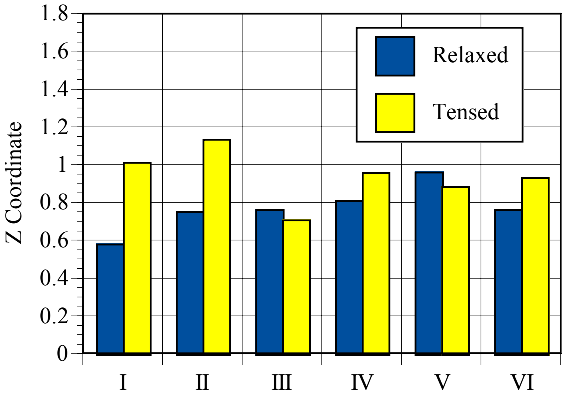


Fig.16 Forehead Rearward Impacts：IAR-Z position of C5/C6 at the time of maxium compressive strain at posterior edge of C5/C6 facet joint (six volunteers ： C6 local coordinate system

The maximum flexion angle of C3 relative to C4 and the maximum tensile strain at the rear edges of C3/C4 facet joints during chin rearward impact are reduced by the muscle tension. Figure 17 shows the ratio of the maximum flexion angle of upper intervertebral disc relative to lower intervertebral disc in tense state of muscle, versus that in relaxed state of muscle during chin rearward impact of each subject. Figure 18 shows the ratio of the maximum tensile strain at the rear edge of upper facet joint in tense state of muscle, versus that in relaxed state of muscle during chin rearward impact of each subject. Every intervertebral disc flexion angle is suppressed by the muscle tension, but this effect for C3/C4 is smaller than those at other intervertebral disc motions. A similar tendency is found also in terms of maximum tensile strain. The connected region of C3 and C4 is the inflection point of cervical spine S-shape deformation, where C3 flexes and C4 extends relative to C7, but each cervical muscle has the only function of extension or flexion. Therefore, it would be difficult to suppress motions in different directions simultaneously, resulting in smaller effects of muscle tension on the suppressions of flexion and the tensile force at the rear edges of C3/C4 facet joints than those at other facet joints.

As discussed in the foregoing, the intervertebral motions and facet joint strains - considered as causes of minor neck injuries - were not suppressed markedly by the muscle tension. In some cases, the strain of cervical vertebral motion became greater with the upward travel of IAR position due to the increase in muscle tension. Therefore, the effect of muscle tension on the suppression of neck injury incidence was not so significant, but it could even increase the possibility of neck injury incidence.

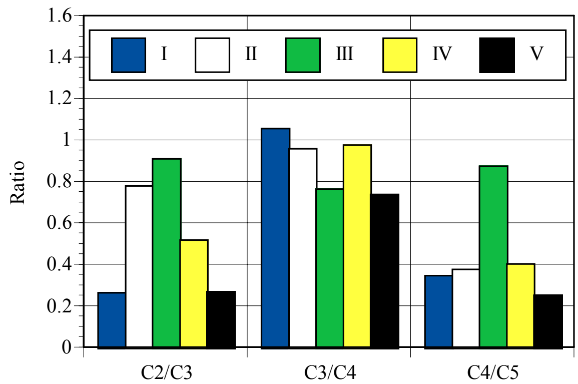


Fig.17 Chin Rearward Impact ： ratio of maximum flexion angles of the tensed state compared to the relaxed state conditions for each volunteer

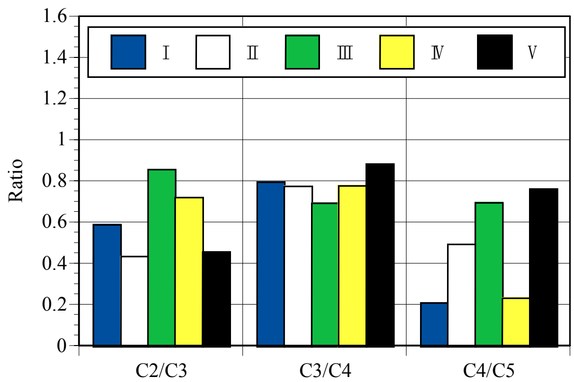


Fig.18 Chin Rearward Impact ： ratio of maximum tensile strains at posterior edge of facet joint on the tensed state compared to the relaxed state condition for each volunteer

IMPORTANCE OF EVALUATING NECK INJURY OCCURRENCE BASED ON SEGMENTAL CERVICAL VERTEBRAL MOTIONS: By comparing the head/neck and cervical vertebral motions under the tense and relaxed states of muscle, it is found that segmental cervical vertebral motions - an important factor for the occurrence of minor neck injuries - were not suppressed by the muscle tension despite the fact that head/neck motions were suppressed markedly by the muscle tension. NIC is calculated from the velocity and acceleration of the head center of gravity relative to the torso. The NIC value based on the head/neck motions constitutes a present evaluation index for neck injuries. The NIC value, the present evaluation index, became smaller by the muscle tension, showing a similar tendency to that of the strains at the rear edges of facet joints in chin rearward impacts. However, the moment when the NIC value became maximum did not coincide with the moment found from the evaluation of strains at the rear edges of facet joints. It is also impossible with NIC to evaluate how much such strains can be suppressed by the muscle tension. On the other hand, the neck injury evaluation by means of IV-NIC based on the motions of facet joints and the strains at the rear edges of facet joints yielded the results shown in Figures 14 and 15. That is, the region and timing of reaching the maximum value and the intervertebral disc rotational angle at that timing agreed with the results shown in Figures 14 and 15. It is hence considered that the IV-NIC is effective also as a biomechanical evaluation index for minor neck injury. It is suggested according to the results of clinical/pathological studies that damages of soft issues and rupture of facet capsules occurred by extreme compressions of cervical vertebral motions, which were major causes of neck injuries (Yoganadan et al., 2001; Cusick et al., 2001; Adam et al., 2004). Since the IV-NIC is based on such findings of cervical vertebral motions, its evaluation accuracy is also deemed high.

As described so far, the present neck injury criterion based on the head/neck motions would not allow an adequate evaluation of injury incidence. On the other hand, the evaluation of neck injuries based on the strains and the evaluation with the IV-NIC based on the segmental cervical vertebral motions, which have been used under this study, are considered important and necessary.

LIMITATION OF THIS STUDY: Injury criteria for minor neck injuries, commonly known as soft tissues injuries or whiplash associated disorders, are not still clarified. Especially in this paper, motion patterns of cervical intervertebral disc and facet joints due to different muscle conditions by an impact directly to the head were analyzed. The possibility of the neck injuries due to facet joint impingement or capsular stretch was argued from the patterns of cervical vertebral motions. On the other hand, the possibility of the neck injuries due to the facet joint impingement and capsular stretch are reported on Ono et al. (1997), Ueta et al. (1998), Yoganadan et al. (2001), and Panjabi et al. (2004). However, the set of experimental data is insufficient to make a generalization based on the results because the subjects were limited only to ten male volunteers. Since the force that was applied to simulate the impact that causes neck injury was minimized for the safety of the volunteers, the results of this research cannot be extrapolated to neck injuries where the level of impact is higher than what is applied in the study.

CONCLUSIONS

By conducting low level direct head impact loading experiments on volunteers that simulated the impact pattern of airbag deployments, the following findings have been obtained based on the quantitative analysis of intervertebral disc and facet joint motions done by means of strains.

1) It is deduced that a minor neck injury occurs due to an extreme compression applied at the rear edges of C5/C6 facet joints and an extreme tension applied to the rear edges of C3/C4 facet joints during forehead rearward impact. The validity of the above result has been verified by comparing the data with clinical knowledge and findings.
2) By comparing the head/neck and cervical vertebral motions under the muscle relaxed and tense state, it is found that the cervical vertebral motions cannot be suppressed by the muscle tension, despite the fact that head/neck motions are suppressed markedly.
3) As for the existing neck injury evaluation index like NIC, the head motion relative to T1 is

analyzed and evaluated. However, it is observed that it is insufficient for the evaluation of the local motion of cervical vertebrae, though it is necessary to evaluate the total kinematics of neck showing the S-shape between head and torso. The more comprehensive index of neck injury evaluation based on local motion of cervical vertebral such as IV-NIC applied in this research is appropriate and found to be important.

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