CERVICAL VERTEBRAL MOTIONS AND BIOMECHANICAL RESPONSES TO DIRECT LOADING OF HUMAN HEAD

Koshiro Ono [1)] , Koji Kaneoka [2)] , Shinichiro Hattori [3)], Sadayuki Ujihashi [3)] ,
Erik G. Takhounts [4)] , Mark Haffner [4)], Rolf H. Eppinger [4)]
1) Japan Automobile Research Institute - Japan
2) University of Tsukuba - Japan
3) Technology Institute of Tokyo - Japan
4) National Highway Traffic Safety Administration – USA

ABSTRACT

There is very little known data characterizing the biomechanical responses of the human head and neck under direct head loading conditions. However, the evaluation of the appropriateness of current crash test dummy head/neck systems is easily accomplished. Such an effort, using experimental means, generates and provides characterizations of human head/neck response to several direct head loading conditions.

Low-level impact loads were applied to the head and face of volunteers and dummies. The resultant forces and moments at the occipital condyle were calculated. For the volunteers, activation of the neck musculature was determined using EMG. In addition, cervical vertebral motions of the volunteers have been taken by means of x-ray cineradiography. The Ethics Committee of Tsukuba University approved the protocol of the experiments in advance. External force of about 210 N was applied to the head and face of five volunteers with average age of 25 for the duration of 100 ms or so, via a strap at one of four locations in various directions: 1) an upward load applied to the chin, 2) a rearward load applied to the chin without facial mask, 3) a rearward load applied to the chin with the facial mask, and 4) a rearward load applied to the forehead. The same impact force as those for the human volunteers was also applied to HY-III, THOR and BioRID.

It is found that cervical vertebral motions differ markedly according to the difference in impact loading condition. Some particular characteristics are also found, such as the flexion or extension of the upper cervical vertebrae (C0, C1 and C2) or middle cervical vertebrae (C3-C4), showing that the modes of cervical vertebral motions are markedly different among the different loading conditions. It is also found that the biofidelity of dummies to neck response characteristics of the volunteers at the low-level impact loads is in the order of BioRID, THOR and HY-III. It is relevant in this regard that the BioRID dummy was designed for a low-severity impact environment, whereas THOR and HY-III were optimized for higher severity impacts.

Key words: Dummies, Neck, Biofidelity, Human Body, Cervical Vertebrae

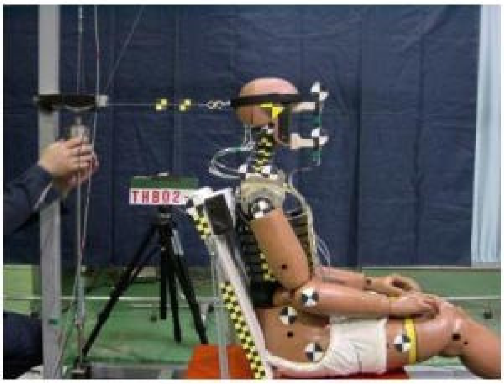
IT HAS BEEN REPORTED (Agaram et al., 2001) that an extremely large shear force and bending moment are observed particularly in the HY-III dummy despite the absence of significant neck bending deformation, where the impact of airbag deployed below the chin of the dummy is transmitted to the neck in crash testing.

The human neck is an extremely complex structure, with various ligaments, intervertebral disks and muscles connecting around the bottom of skull and the top of cervical spine - i.e. occipital condyle (OC) joint - and joints among individual cervical vertebrae, which control their motions. The HY-III dummy neck, on the other hand, has an elastic column molded with hard rubber, which connects the head and neck, and acts as the substitute to simulate the human neck. The human OC joint is highly flexible, with the mobility of 10 - 20 or greater degrees in flexion and extension (White & Panjabi, 1990). Due to such a complex structure, human neck injuries take various forms (Benoist, 1998; Croft, 1995).

Considering the mechanism of human neck injuries, it will be necessary to take into account the complex characteristics of OC joint surrounded by various ligaments, muscles connecting the head and neck, and intervertebral disks among individual cervical vertebrae, and to incorporate them into the characteristics of dummy neck joints. At the same time, it is required to evaluate the injury parameters with a more accurate yet simpler approach, in order to develop "crash dummies" as easy-to-use and practical tools for the evaluation of human injuries that may occur in vehicle collision.

Under such circumstances, it was decided to determine human head/neck impact responses more clearly in this study, and to pursue proper structures and characteristics of "crash dummies" capable of more faithful simulations of human neck characteristics.

To be specific, it was then decided to conduct simplified impact experiments assuming the interference between the activated airbag and the head/neck of dummy in crash testing, by applying low-level impact loads to each volunteer in four directions: 1) upward impact against the chin, 2) rearward impact against the chin, 3) rearward impact against the entire face (head) wearing a facial mask in a proper direction that the impact would pass through the head center of gravity, and 4) rearward impact against the forehead, in order to examine the human head/neck impact responses. Moreover, it was also decided to conduct the same impacts on the HY-III, THOR and BioRID dummies to find the differences in impact responses from those of humans.



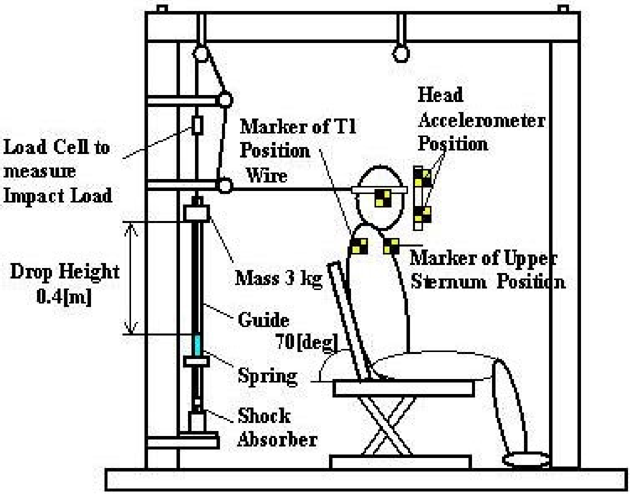


Fig.1 Test set-up

EXPERIMENTAL METHODS

SUBJECTS (VOLUNTEERS) AND INFORMED CONSENT: Five healthy adult male volunteers of average age 25 without any history of neck injury have participated in the experiments as the test subjects. It was confirmed through the X-ray photographs that the volunteers have not shown any signs of cervical spine deformations. For the motion observation tests, four of five subjects have participated.

The experimental protocol was reviewed and approved in advance by the Ethics Committee of Tsukuba University. All volunteers submitted their written informed consent in accordance to the Helsinki Declaration (WHO/CIOMS, 1988) prior to the implementation of the experiments. The height, weight, sitting height, estimated head weight and estimated head inertial moment of each subject are shown in Table 1 together with the age and sex. To determine differences in characteristics due to the varying in dummy head/neck structures, the HY-III, THOR (Haffner et al., 2001) and BioRID (BioRID II Final Report, 2001) dummies have been also used in the experiments.

Table 1 Subjects

		Age	Sex	Height (cm)	Sitting Height (cm)	Weight (kg)	Estimated Head Weight (kg)	Estimated Inertia of Head (10*5 g-cm*2)
1	SH	23	M	171	89	65	4.12	2.17
2	YY	20	M	172	89	60	4.04	2.08
3	NY	21	M	177	91	75	4.57	2.37
4	HI	22	M	174	93	70	4.68	2.44
5	KK	38	M	172	92	72	4.58	2.42
6	HY-III	-	-	-	-	78	4.68	2.44
7	THOR	-	-	-	-	78	4.61	2.21
8	BioRID	-	-	-	-	78	4.68	2.44

TEST SETUP

Assuming various head impacts with airbag, the following four impact loading directions and locations were selected.

1) Upward load applied to chin (hereafter called "upward chin" or “C”)
2) Rearward load applied to chin (hereafter called "rearward chin" or “L”)
3) Rearward load applied to head wearing a mask, with the impact loading line passing through the head center of gravity (hereafter called "rearward mask" or “M”), and
4) Rearward load applied to forehead (hereafter called "rearward forehead" or “U”).

Figure 1 shows the conditions of impact forces applied to the head/neck of volunteers and dummies. Load was applied to the head or face of each subject/dummy by freely dropping a three-kg weight along the guide from the height of 40 cm. The head or face of each subject/dummy was roundly strapped by a webbing belt or facial mask connected to a thin steel wire in order to apply the impact. The weight stopping distance was adjusted to about 10 cm using an elastic spring to control the duration of impact acceleration. The impact loads were measured with the load cell attached to the wire. The sitting height adjustable seat was made of a rigid steel. The sitting height adjustable seat was made of a rigid steel. The sitting position was set at standard position (with seatback angle of 20 degrees), while the neck muscle condition of each volunteer was set under two different states - tense and relaxed states.

INSTRUMENTATION: The instrumentation used during the tests is listed in Table 2. The four-channel acceleration measurement method (Ono & Kanno, 1993) was applied during the tests to analyze shear force, axial compression force and bending moment applied to the upper portion of neck (occipital condyle: OC). See Ono (2001, 1997) for the details of the acceleration measurement methods for the head and T1, the EMG measurement, and the analysis of head/neck motions and neck forces around OC. The right-handed coordinate system (SAE J211) of reference was used.

CINERADIOGRAPHY: The radiation probe of the cineradiographic system (Cine-system: Philips BH5000; cine-camera: Attitechno 35) was capable of rotating 180 degrees on the horizontal plane around the system column. The probe alone could be also rotated by +/- 180 degrees, but the vertical height was not adjustable. Therefore, a steel chair capable of electric height adjustment was fabricated so that the cervical vertebrae of volunteer could be set within the X-ray radiation range as shown in Figure 2 by modifying a height adjustable cargo carrier. The cervical vertebral motions within the radiation range were taken at the speed of 60 frames per second by means of a digital X-ray cineradiography. The X-ray exposure was set at 0.016 mG (milli. Glay) per frame, and about 20 frames could be taken per one impact.

Table 2 Measurement Items

Locations		Items	Axis	Model
Event		Trigger	-	Conatct switch
Impact Load		Load	x	LUR-A-1KNSA1
Volunteer	Head - Upper	Acceleration	x, z	Endevco 7264A (20G Cal.)
	- Lower	Acceleration	x, z	Endevco 7264A (20G Cal.)
	T1	Acceleration	x, z	Endevco 7264A (20G Cal.)
	EMG	Control	Skin	
		SCM(L)	Sternoclaidmastoid muscle (Left)	
		PVM(L)	Paravertebral muscles (Left)	
		TZ(L)	Trapezius muscles (Left)	
		SCM(R)	Sternoclaidmastoid muscle (Right)	
HY-III THOR BioRID	Head - Upper	Acceleration	x, z	Endevco 7264A (20G Cal.)
	- Lower	Acceleration	x, z	Endevco 7264A (20G Cal.)
	Head - C.G.	Acceleration	x, y, z	Endevco 7264A (20G Cal.)
	T1	Acceleration	x, z	Endevco 7264A (20G Cal.)
	Upper neck	Bending moment	My	Denton 2564
		Axial force	Fz	Denton 2564
		Shear force	Fx	Denton 2564

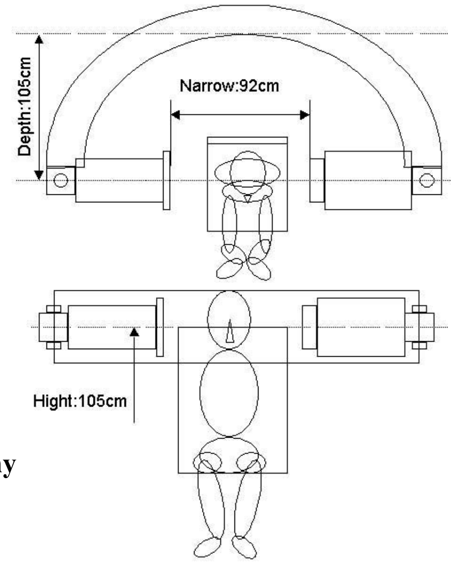


Fig.2 X-ray Cineradiography

CERVICAL VERTEBRAL IMAGE ANALYSIS: Each cervical vertebral image digitally photographed by the cinecamera was analyzed. The still photograph of initial state shown in Figure 3 was used first to prepare a template showing the form of each vertebra, using an image analysis system (CANVAS 7.02 made by Denobe System Inc.). Such templates were coincided accurately with the corresponding cervical vertebral images undergoing changes over time, in order to determine the coordinates of anterior/posterior facet points of each lower and upper vertebrae and intervertebral disk, and to calculate the rotational angle, vertical displacement and slip among individual intervertebral joints from the coordinates (see Figure 3).

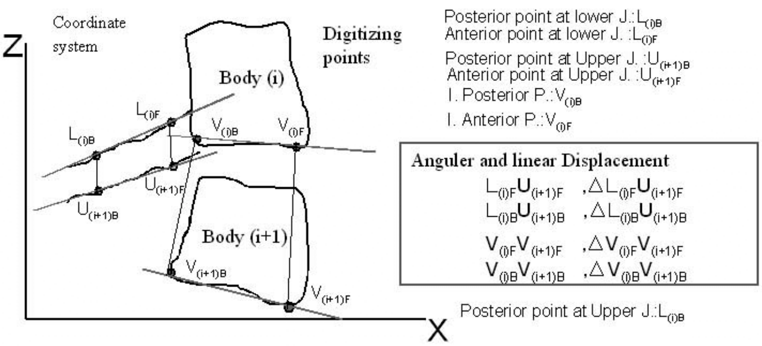


Fig.3 Analysis of Cervical Vertebral Motion

RESULTS

HEAD/NECK KINEMATICS: Figure 4 shows the example of the time histories of the head impact loads for volunteers and dummies in the rearward chin impact condition. Figure 5 shows the comparison of time histories of the head rotation angles among the volunteers and the dummies in rearward chin impact condition. The mean values of the four volunteers are plotted in the time history diagram of head rotation angles.

In the case of volunteers, the rearward forehead impact pattern is similar to those of rearward mask and upward chin impacts. However, the rise of head rotation angle is sharper for the upward chin impact than those of the rearward forehead and rearward mask impacts. On the other hand, in the HY-III dummy, the rise of head rotation angle is sharper for the rearward forehead impact than that of upward chin impact.

For the rearward mask impact, the head rotation angles of the volunteers are similar to those of rearward forehead impacts except for the flexion found in the initial stage of impact. While, for the HY-III dummy, some differences are observed in peak timing of head rotation angle, but the end of upper neck such as the cantilever elastic body is either pulled, bent and deformed in every case of impact. The biofidelity of dummy head rotation angle pattern compared to those of volunteers is in the order of BioRID, THOR and HY-III dummies. For every dummy, the peak value of head rotation angle is smaller and the time to reach that peak value is shorter than those of volunteers.

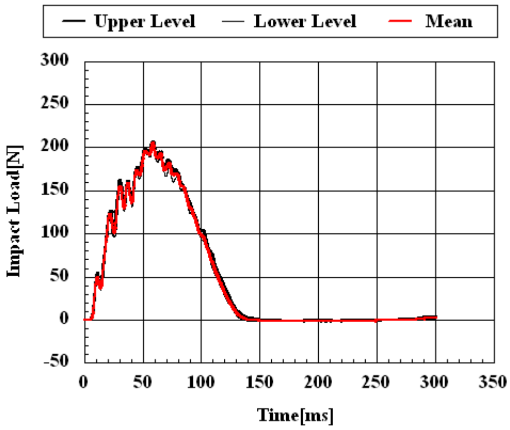


Fig.4 Example of time histories of the head impact loads for volunteers and dummies (Chin-up)

COMPARISON OF CALCULATED AND MEASURED NECK LOADS: Neck loads around human occipital condyles could not be measured directly. Therefore, a validation of the method to calculate the neck loads according to the acceleration data measured at the volunteers' heads was conducted. See Ono et al. (2001) for the details of validation method. The results of validation are satisfactory as the maximum difference from the measured values is about 10 %.

COMPARISON OF NECK IMPACT RESPONSES BETWEEN RELAXED VOLUNTEERS AND DUMMIES: Comparisons of neck impact loads between the volunteers and the dummies are shown in Figures 6 through 9. The results of comparison are shown separately for the HY-III, THOR, BioRID, and the mean value of four relaxed volunteers, and their maximum/minimum values are also added separately in individual figures.

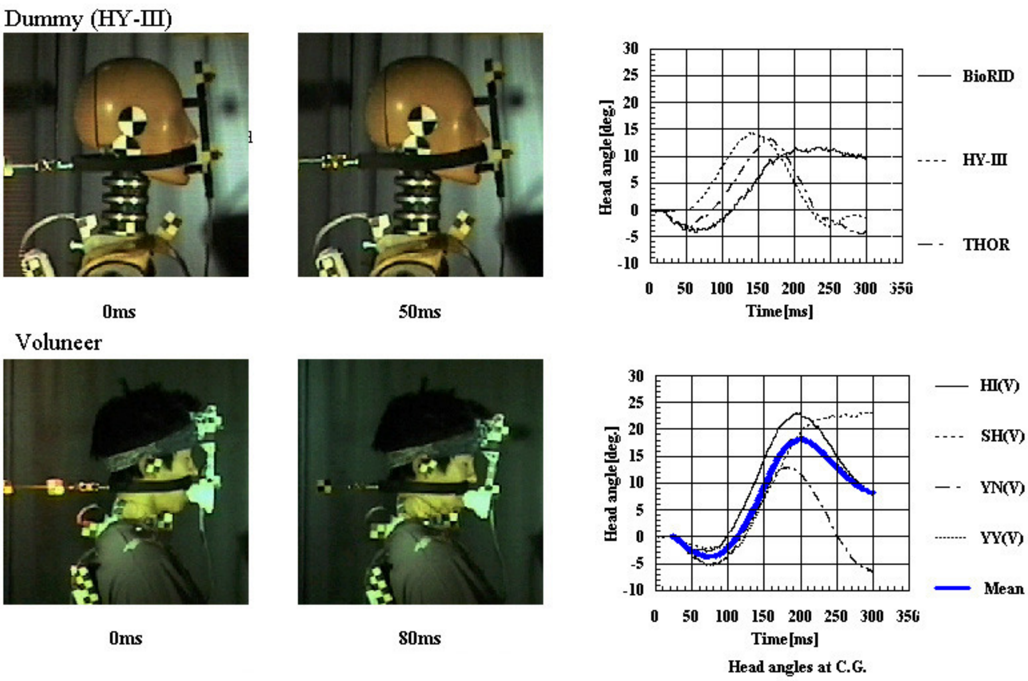


Fig.5 Comparison of head angles among dummies and volunteers by high-speed video

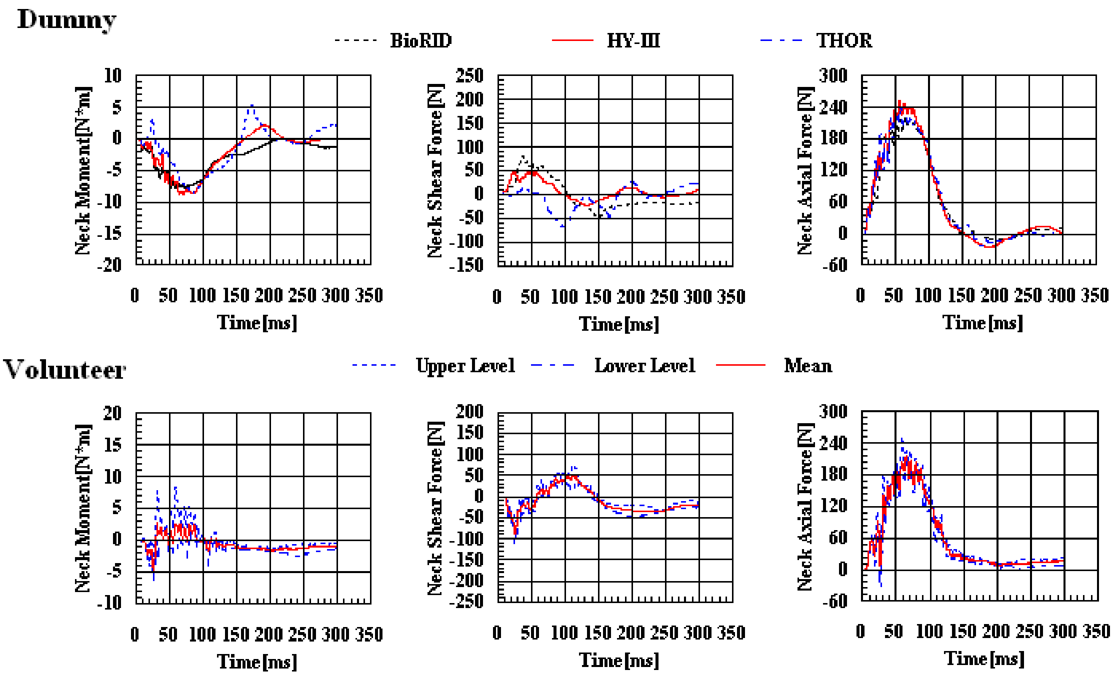


Fig.6 Comparison of neck moment and forces between dummies and volunteers under the condition of upward load applied to chin (C)

<u>Upward Chin Impact:</u> The comparison of neck loads in the upward chin impact is shown in Figure 6. The neck moments of the dummies are twice or more greater than those of the volunteers, and their phases are reversed. The human necks flex slightly then extend, with the neck moments continue for long periods of time without reduction. This tendency becomes more significant in neck shear force. When the human chin is pulled upward, the neck shear force acts on the occipital condyle in rearward direction, then the head rotates rearward, and the OC is pulled forward by a shear force that continues for some time. Such motions are not observed in the dummies, but a shear force acts on the neck joint as the link to pull the neck forward. The neck axial force pattern is similar between the human subjects and the dummies.

<u>Rearward Chin Impact:</u> As shown in Figure 7, some phase differences are found between the human subjects and the dummies. Thus, the processes of neck moments and shear forces of dummies changing over time are also different from those of human subjects. This tendency is roughly the same among the HY-III, THOR and BioRID dummies, but the differences from the human subjects are not so significant as in the case of upward chin impact. For human subjects, there are various types of soft tissues located between the chin and the neck upper portion, which presumably restrain the head rotation when an impact is applied rearward from the chin. In this condition, it results in a greater moment around the OC. Hence, it will be necessary to apply an impact force against a proper region of human subject where such a moment to the OC can be avoided as much as possible, in order to determine the human OC joint flexibility in such an impact.

<u>Rearward Mask Impact:</u> According to the rearward chin impact described in the foregoing, the following test is deemed necessary for the contribution of the flexibility of OC joint. Namely, distributed force impact should be conducted against a region of head where the bending moment is not likely to act on the OC joint while the head is making a linear motion. In this regard, impact tests were conducted with each volunteer wearing a facial mask in such a manner that the head would make a linear motion. Figure 8 shows the comparison of neck loads in rearward mask impact tests. The bending moment is entirely different between the human subjects and the dummies. In the case of relaxed human subjects, hardly any neck bending moment is found due to the mobility of OC joint. It is also found that no significant shear force or axial force is found in the initial stage of impact, but found around 20 to 30 ms after impact. The bending moment of the BioRID dummy is relatively small in comparison to the HY-III and THOR dummies showing large bending moments.

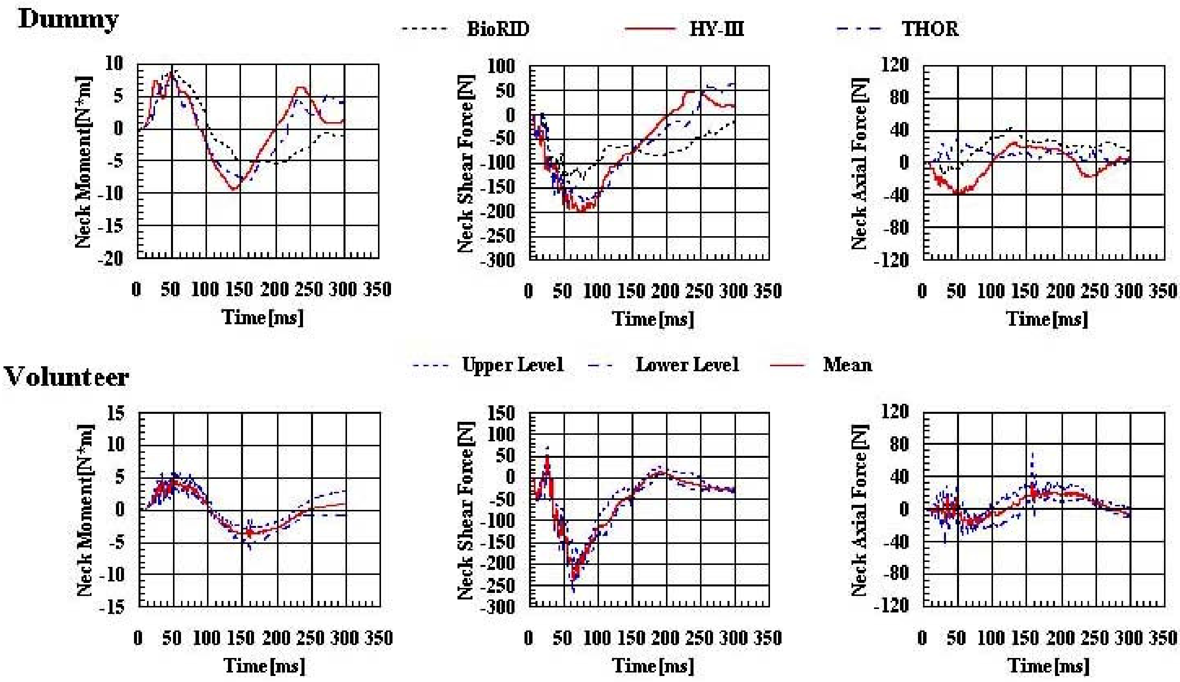


Fig.7 Comparison of neck moment and forces between dummies and volunteers under the condition of rearward load applied to chin (L)

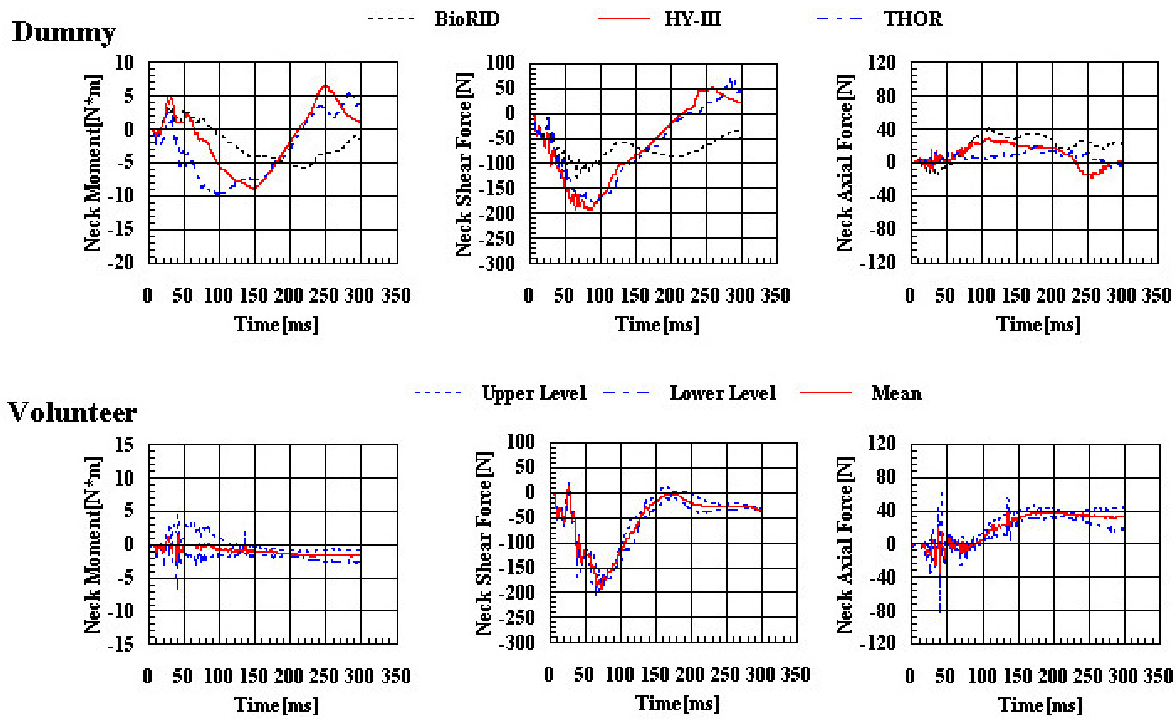


Fig.8 Comparison of neck moment and forces between dummies and volunteers under the condition of rearward load applied to mask (M)

Rearward Forehead Impact: The comparison of neck loads in rearward forehead impact tests is shown in Figure 9. The phase of bending moment of HY-III dummy is about twice longer and the peak value is about 1.2 time greater than those of human subjects. The THOR dummy also shows a similar tendency, but the peak value is roughly the same as those of the human subjects. The BioRID shows a similar phase tendency to the human subjects, while the peak value is about 0.7 time of human subjects. Some differences in phase and peak value of shear force are also found between the dummies and the human subjects, with similar tendencies to those in bending moment. As for axial forces, it is found that a downward axial force acts on the human OC joint where the forehead is pulled rearward, whereas an upward axial force acts on both THOR and HY-III dummies except for the BioRID dummy.

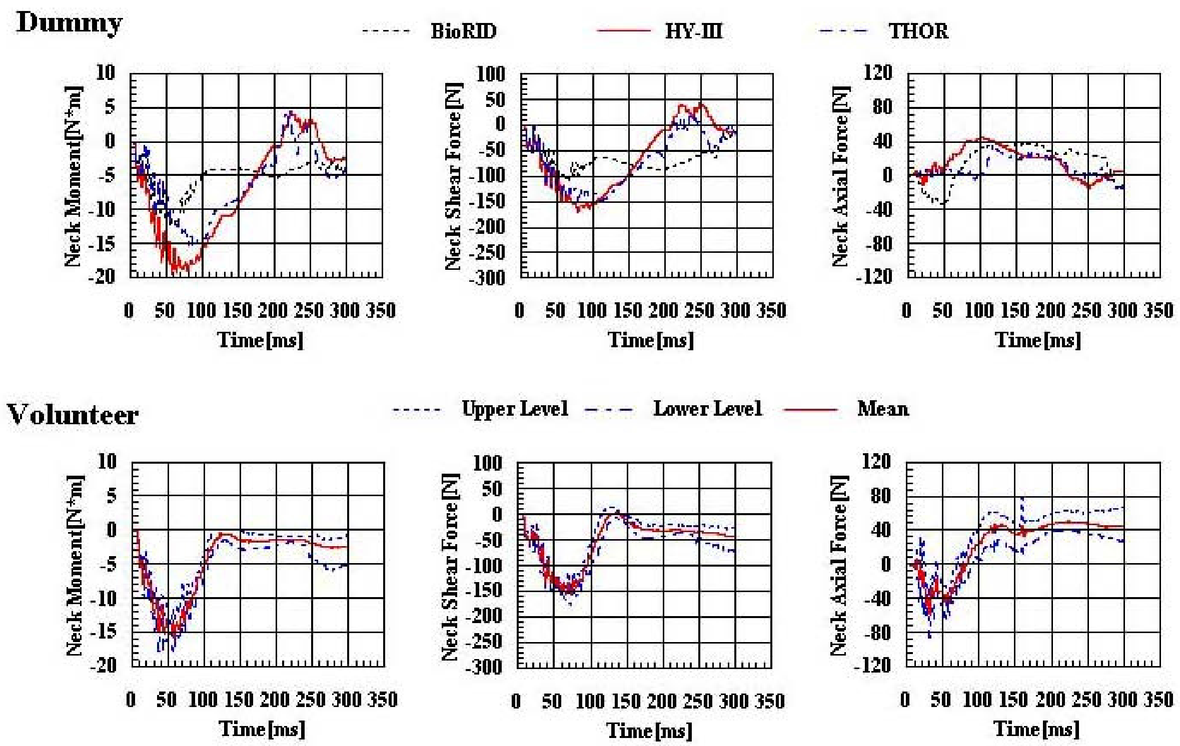


Fig.9 Comparison of neck moment and forces between dummies and volunteers under the condition of rearward load applied to forehead (U)

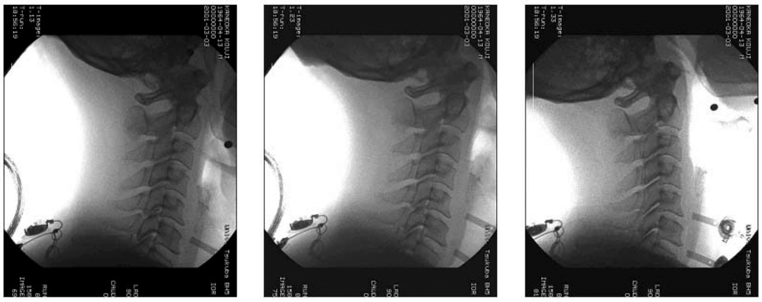
CHARACTERISTICS OF CERVICAL VERTEBRAL MOTIONS: The rotation angle and vertical displacement of each cervical vertebra, and the slip among intervertebral joints are analyzed, using the cervical vertebral images taken by X-ray cineradiography. The time histories of vertebral segment rotations are divided by the forms of impacts, and shown in Figures 10 to 13. Typical motions of cervical vertebrae are divided into two phases - Phase 1 (0 to 100 ms) and Phase 2 (100 to 200 ms) and described in the following.

Upward Chin Impact:

Phase 1 (0 to 100 ms): Cervical vertebrae are subject to large axial forces in tensile direction, with the head accelerating (0-40 ms) and pushed forward (+X). A neck shear force is found in forward direction but the value is small. The neck axial force becomes maximum around 60 ms, but the neck moment is slight (Figure 5). Cervical vertebral motions are as follows - the head (C0) stretches markedly, while C1 and C2 are pushed forward and bent slightly, then start stretching. A relatively large displacement of C1/C2 is found in the stretching direction (Figures 10a and 10b).

Phase 2 (100 to 200 ms): The cervical vertebral motion changes into extension due to the head inertia. In this phase, the change in relative rotation angle between C4-C6 becomes significant, while individual vertebrae of C3 to C6 start stretching and slipping rearward. C1, on the other hand, is slipping forward due to the effect of head rotation (Figures 10a and 10b).

a) X-ray images



0 ms 100 ms 200 ms

b) Typical patterns of motion

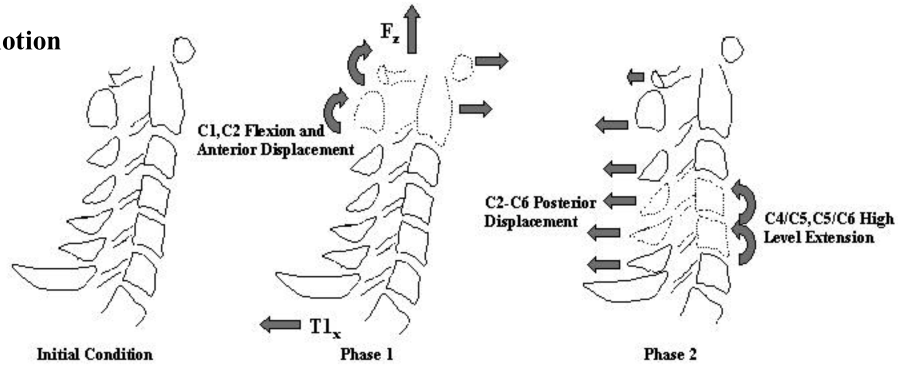


Fig.10 Cervical vertebral motion under upward chin loading condition

Rearward Chin Impact:

Phase 1 (0 to 100 ms): In the initial stage of impact, the head bending rotation starts, accompanying a large rearward neck shear force and a large bending moment (Figure 7). The C0, C1 and C2 are flexion around 30 ms and reach the peak around 100 ms. The torso moves slightly forward - opposite direction to the head - which coincides with the neck shear force. The head (C0) and C1 start flexion motion, while the lower vertebrae C4-C7 start extension (S-shape deformation) (Figure 11a and 11b). The C1-C4 show a relative flexion motion due to the moment acting in the flexion direction, and the rearward slip of C1 becomes larger due to the shear force acting on the neck. The vertebrae C2-C3 slip forward.

Phase 2 (100 to 200 ms): Upon termination of impact, the motion of head changes into rotation in the extension direction. The motion of C1-C4 with the relative flexion rotation caused by bending also changes into the direction of extension due to the head inertia. As for the linear displacement, the cervical vertebrae that make forward relative motion in phase 1 due to the flexion changes into the rearward relative linear motion due to the neck extension (Figures 11a and 11b).

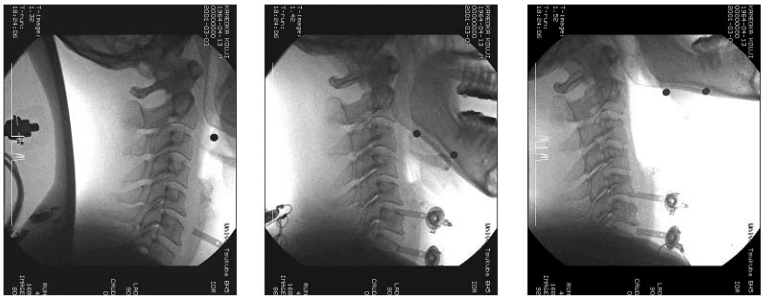
Rearward Mask Impact:

Except for a relatively small flexion motion of the upper vertebrae in comparison to 2) above, the overall tendency is the same. Hence the detailed descriptions are omitted here.

Rearward Forehead Impact:

Phase 1 (0 to 100 ms);With the rearward shear force and the moment in the extension direction acting together, the moment and the head rotation angle become the largest among the three cases of impacts (Figure 8). The torso slightly moves in the direction opposite to the head motion as in other cases of impacts. The overall motion of the head and cervical vertebrae is extension. However, C4-C7 contributes greatly to the overall extension of cervical spine, whereas C0-C3 extends slightly. Compared with the chin upward impact, the relative rotation of head (C0) is smaller. The observation of linear/vertical displacements of cervical vertebrae shows mainly the rearward slip (Figure 12a and 12b).

a) X-ray images



0 ms 100 ms 200 ms

b) Typical patterns of motion

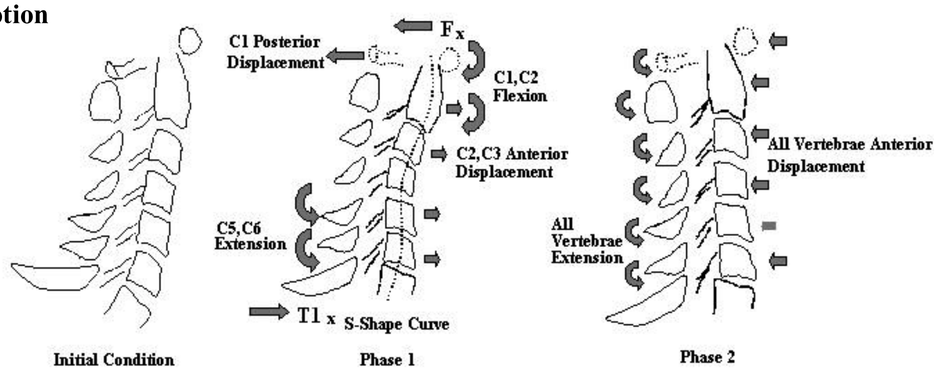
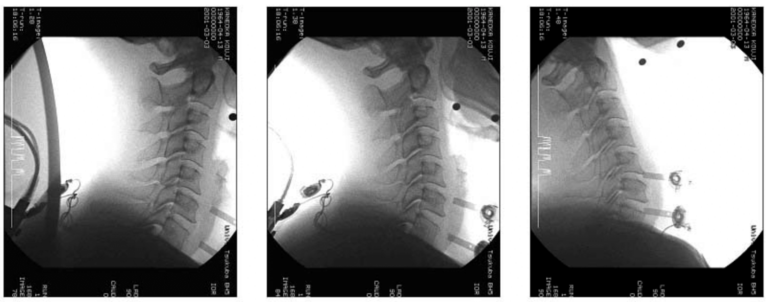


Fig.11 Cervical vertebral motion under rearward chin loading condition

a) X-ray images



0 ms 100 ms 200 ms

b) Typical patterns of motion

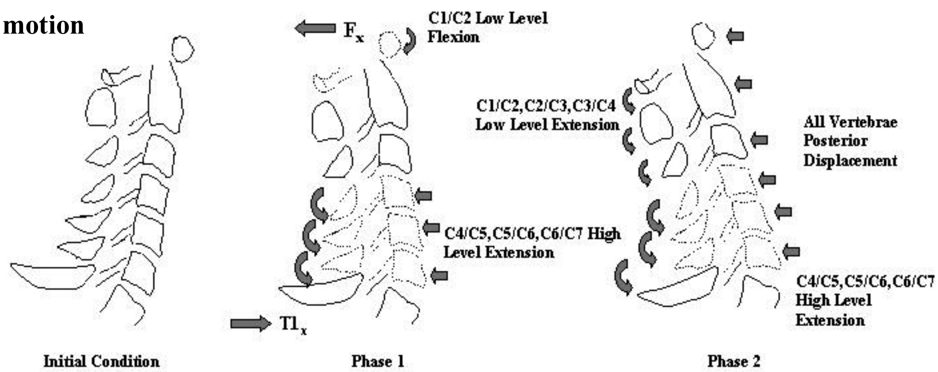


Fig.12 Cervical vertebral motion under rearward forehead loading condition

Phase 2 (100 to 200 ms); The head and neck extend further due to the head inertia after the termination of impact. The relative rotation angles among C4-C6 become greater, while the angles become smaller among C1-C3 as in the case of phase 1. The rearward slip between C4/C5 and C6/C7 becomes the greatest among the three cases due to the extension (Figures 12a and 12b).

DISCUSSION

COMPARISON OF HEAD/NECK IMPACT RESPONSES BETWEEN RELAXED HUMAN SUBJECTS AND DUMMIES: The same set of impacts were applied to both the human subjects and the three types of dummies (HY-III, THOR and BioRID), in order to find differences in impact responses between the two types of subjects. It may be said that the human neck impact responses are influenced markedly by the loads applied to the OC joint according to the direction of impact force and the location subjected to impact, as well as by the OC flexibility. The biofidelity of the dummies in terms of the moments, shear forces and axial forces applied to the necks of the human subjects and the dummies are summarized as follows.

<u>Upward Chin Impact:</u> The neck moments of the dummies are about twice greater than those of the human subjects, and their phases are reversed. As regards the shear forces, a rearward shear force acts first to the human OC as the chin is pulled upward, then a forward shear force acts next. Such motions are not found in the dummies - only the forward shear force acts against the OC which functions as the link when the chin is pulled upward.

<u>Rearward Chin Impact:</u> The phase, neck moment and time history of shear force are different between the human subjects and the dummies. Such differences are, however, not so significant as in the case of upward chin impact. In the case of human subjects, it is presumed that the soft tissues located between the chin and neck upper portion restrain the head rotation when the rearward impact is applied to the chin.

<u>Rearward Mask Impact:</u> The neck moment is entirely different between the human subjects and the dummies. Any neck moment is hardly found in human subjects due to the mobility of OC joint. Also, any significant shear force or axial force is not shown in the initial stage of impact, whereas such forces occur around 20 to 30 ms after impact. As for the dummies, the neck moment of BioRID is smaller than other dummies, which show rather large neck moments.

According to the foregoing findings, it may be said that the human neck impact responses are influenced markedly by the direction/location of impact force and the load applied to the OC joint, as well as by the mobility of the OC joint. The qualitative biofidelity of the dummies in terms of human impact responses for low-severity impacts is in order of BioRID, THOR and HY-III.

<u>Rearward Forehead Impact:</u> The neck moment of HY-III dummy is greater and the duration is also longer than those of the human subjects. The shear force of the dummy is similar to that of human subject, but the duration is longer. The axial force of the BioRID dummy is similar to those of the human subjects, but it is smaller for other two kinds of dummies, which are presumably caused by the difference in cervical spine alignment (Ono et al., 1997) between the human subjects and the dummies.

EFFECT OF NECK MUSCLE CONDITIONS: The physical quantity influenced most by the tensed condition of neck muscle is the head rotational angle. The reduction of head angle compared with the relaxed condition is 45 % in the upward chin impact, 61 % in the rearward chin impact, 71 % in rearward mask impact, and 46 % in the rearward forehead impact (Figure 13). The difference between tensed and relaxed neck muscle conditions is about 10 % in terms of neck load, about 15 % in acceleration at the head center of gravity, and about 10 % in TI acceleration, showing that the effect of neck muscle condition is small. In terms of head angle, however, the difference is significant as stated earlier. Hence, it can be deduced that not only the effect of main muscular tissues connecting the head and neck should not be ignored, but as well as the effects of localized muscles and the ligaments around the upper cervical vertebrae must also be considered.

PATTERNS OF FACET JOINT STRETCH DUE TO DIFFERENT IMPACT CONDITIONS: It is said at present that causes of neck injuries include the localized motion of cervical vertebra body causing the injury with the impingement of facet joint (Ono et al., 1997), opening of the posterior facet joint due to the rotation and sliding of cervical vertebra body causing the stretch of capsular ligaments (Nightingale et al., 1997) , and the stretch of capsular ligaments just before the maximum head rotation has been occurring (Deng et al., 2000), which contribute markedly to the occurrence of neck injuries. In this regard, it would be vital to use the localized motion of cervical vertebrae as an index for the risk of neck injuries.

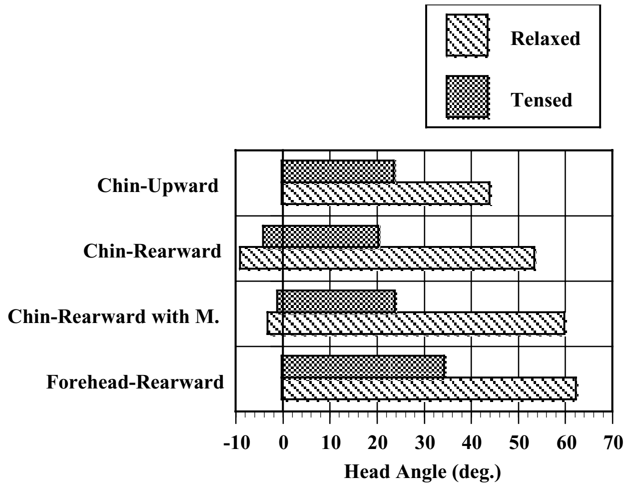


Fig.13 Ranges of head angles under the relaxed and the tensed muscle conditions

Hence, the strain of each facet joint is compared and reviewed between the normal condition and the impact condition for the quantification of localized motions of facet joints. Figure 14 shows the strain of posterior facet joints of the impact, in reference to the maximum strain in the normal condition. The "normal condition" refers to the spontaneous flexion or extension motion in human subject - that is, motion of 42 degrees in terms of head rotation angle in extension, and 12 degrees in flexion. As the locations of C0, C1 and C2 facet joints have not been put into numerical values due to undefined template of images, they are excluded from the analysis conducted under this study.

In the upward chin impact, a strain is found in the expanded direction of C2/C3 due to the momental flexion motion in the former half of impact, which is different from the posterior facet joint motion found in the rearward forehead impact. On the other hand, compressive strains are found among C3-C6. The comparison of both types of strains reveals that the rearward forehead impact shows greater values at individual cervical vertebrae levels, with the ratios of C3/C4 (1.04), C4/C5 (1.63), C5/C6 (1.29) and C6/C7 (1.73) respectively.

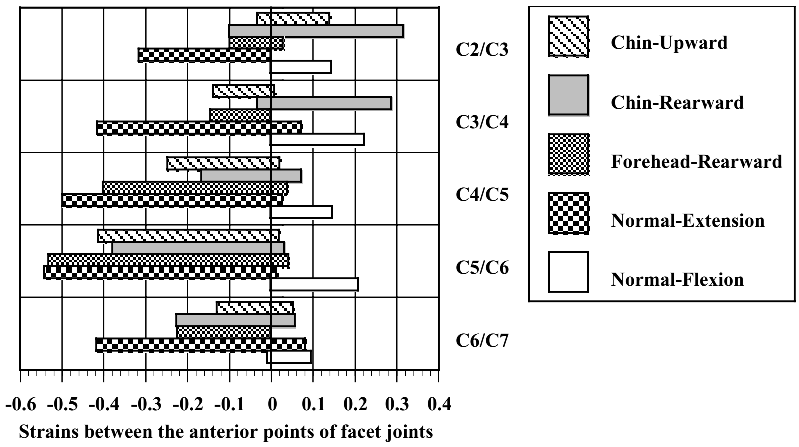


Fig.14 Strains between the anterior points of lower and upper facet joints

In the rearward chin impact, strains are found between C2/C3 and C3/C4 in the expanded direction due to the S-shape deformation. At cervical vertebral levels below C4, compressive strains are found. In comparison with the rearward forehead impact, the ratios are as follows - C4/C5 (0.41), C5/C6 (0.71) and

C6/C7 (1.01) respectively. In comparison with normal conditions, strains at C2/C3 and C3/C4 in expanded direction for the rearward chin impact are with the large ratios of C2/C3 (2,18) and C3/C4 (1.28), showing the occurrence of abnormal motions. This is presumably due to the flexion moment acting on the upper cervical spine that causes excess flexion motions and rearward extension of posterior facet joint, which in turn increase the stretching strains. These lead to suggest that some risk of neck injury exists between C2/C3 and C3/C4 that are upper cervical vertebrae.

CONCLUSIONS

A decision was made to determine human head/neck impact responses more clearly, by assuming impact loading conditions that would act on the human head by the activation of airbag, based on the biomechanical responses of human head/neck, which may differ according to the differences in impact directions.

The same impacts as those of human subjects were also applied to the three types of dummies (HY-III, THOR and BioRID) to determine how their responses would differ from the human responses. The findings thus obtained are as follows.

1) Impact loads under simulated airbag loading conditions applied to the volunteers and the dummies differ markedly from the impact forces applied to the human subjects or dummies. The effects caused by such differences in impact forces cannot be ignored. However, it has been confirmed that significant differences exist in neck responses between the human subjects and the dummies.

2) The human occipital condyle (OC) joint in particular has a region that can move rather freely against the first cervical vertebra (C1), in which hardly any neck bending moment or shear force is found. This is an important insight for the proper structures and characteristics required of the dummy neck. It is also found that cervical vertebral motions differ markedly according to the difference in impact loading location. The forgoing findings facilitate the determination of factors contributing to the incidence of neck injuries upon airbag impact.

3) The BioRID and THOR dummies are still in the development stage. It is found, however, that the quantitative biofidelity of individual dummies to the low-severity human head/neck impact responses is in the order of BioRID, THOR and HY-III. It is relevant in this regard that the BioRID dummy was designed for a low-severity impact environment, whereas THOR and Hy-III were optimized for higher severity impacts.

4) For the determination of characteristics in human cervical vertebral responses to the direct impact loading against the head, the cervical vertebral motions are compared between normal state and upon impact, and the strains in posterior facet joints are noted. Consequently, some particular characteristics are found, such as flexion and extension of the upper cervical vertebrae (C0-C1-C2) or middle cervical vertebrae (C3-C4) showing that the modes of cervical vertebral motions are markedly different.

5) A expanded strain which is 2.18 time greater than that in normal condition is found at the posterior facet joint of C2/C3 in the flexion of rearward chin impact in particular.

6) A compressive strain, which is greater than that in normal condition, is determined clearly at the posterior facet joint between C5/C6 in all impact conditions. It suggests proper structures/characteristics required of the dummy neck capable of more faithful simulations of human head/neck responses and characteristics.

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