Biomechanical Response of Head/ Neck/ Torso and Cervical Vertebral Motion to Lateral Impact Loading on the Shoulders of Volunteers

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ABSTRACT

To understand the response of the head, neck and torso during a lateral collision, and to investigate the relation between cervical vertebral motion and the occurrence of neck injuries, lateral impact experiments were conducted on the shoulder areas of human volunteers. Test subjects consisted of 8 volunteers (5 males and 3 females). For the analysis of cervical vertebral motions of each subject, a cineradiography system was used. A VICON motion photographic device was also used for the three-dimensional analysis of head/neck/torso motions. In the experiment, 3 levels of impact force (400N, 500N, and 600N) were applied considering both the presence and absence of muscle tension.
Cervical vertebral rotations all started at 35 ms, but the time required to reach the peak rotation increased toward the upper vertebrae, with C7 and T1 peaking at 120 ms and the final peak in the head at 120 ms. At around 35-80 ms, the rotation angle of C5 surpassed those of the head and C4 showing that the cervical spine was bending into an S-curve. This phenomenon shows the same type of cervical vertebral motions causing whiplash during a rear-end collision. Also, extreme compression was at work in the vertebral disc and/or the facet joint in C6/C7 and C7/T1, suggesting a high probability of injury occurring in the neck.

INTRODUCTION

Vehicle occupants involved in automobile accidents but saved from fatality with injury severity level reduced to serious - minor are increasing, owing probably to the implementation of automobile safety measures and advances made in emergency medical treatments. It can be deduced that the increase in number of those with severe - minor injuries is attributable to the abovementioned developments. In order to keep pace with this development, active studies are being made for further enhancement of automobile safety, particularly against vehicle frontal collisions. Despite such efforts, the number of those injured by rear-end collisions is increasing significantly (Kraft et al., 2002), which is considered by some researchers as a "trade-off" between the number of fatalities and the number of "severe - minor injuries", with the priority set on the reduction of the fatalities. Regarding neck injuries, such increase were found not only in rear-end collisions but also in lateral-collisions (Hell et al., 2003). The same as in the case of rear-end collisions, the neck injury mechanism in lateral-collisions has not been clearly determined, with many questions still remaining unsolved (Kumar et al., 2005, Ito et al., 2004, Yoganandan et al., 2001). One of the reasons is the scarcity of biomechanical studies conducted on human head/neck/torso impact responses in lateral-collisions. In this regard, a new test equipment called "head/neck inertia impactor" was used in this study in order to analyze the "human head/neck junction" while applying a lateral impact to the shoulder. To be more specific, volunteers were impacted on their shoulders to simulate automobile lateral-collisions, and study human head/neck/torso impact responses as well as cervical vertebral motions. Differences in neck muscle responses between the male and female volunteers were also investigated.

EXPERIMENTAL METHODS

Lateral Inertia Impactor

An inertia impactor (Figure 1) specially designed for this study was used in order to investigate head/neck/torso responses and cervical vertebral motions of subjects submitted to a lateral inertia

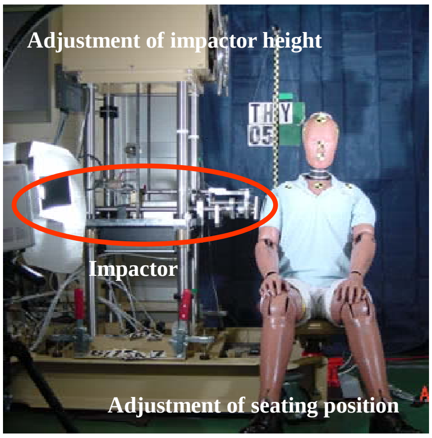

Fig.1 Lateral inertia impactor

impact. The test equipment consists of a compressed air storage/coil spring unit to eject the impactor, the impactor height adjuster, and the test subject sitting position adjuster (forward/ backward & up/down). The front plate, pushed against the impactor front was fixed to the piston through the piston rod. The compressed air is stored in the cylinder with the piston fixed to the air chuck located at the rear end. The impactor mass is 8.5 kg. The impactor is ejected by opening the air chuck, and impact is applied to the back of test subject. A coil spring is provided to control the impactor stroke and the rise of impact load. The stroke setting and the rise of impact load can be varied per test.

Head/Neck/Torso Visual Motions

In order to record the kinematics of the head/neck/torso of each subject during impact, a high-speed video camera with a photographic capability of taking 500 frames/s was used. The head rotation 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 according to the photographic images. A VICON motion photographic device (125 frames/s) was also used for the three-dimensional analysis of head/neck/torso motions.

Table 1 Anthropometric data of the subjects

	Age	Sex	Height (cm)	Weight (kg)	Sitting Height (cm)	Mass of head (estimate) (kg)	Inertia of head (estimate) ($10^{-2}kgm^2$)
1	25	M	172	67	97	4.28	2.21
2	23	M	170	63	94	4.14	2.14
3	22	F	162	46	83	3.63	1.85
4	23	F	166	51	88	3.77	1.93
5	24	F	161	58	86	3.98	2.04
6	23	M	180	85	91	4.97	2.59
7	24	M	174	61	90	4.07	2.10
8	24	M	181	77	96	4.64	2.42

Cervical Vertebral Motions Using Cineradiography System

For the analysis of cervical vertebral motions of each subject during impact, a cineradiography system (Philips: BH500) was used. The system is capable of taking cervical vertebral images at the rate of 60 frames per second with 16.67 ms intervals.

Experimental Conditions

Using five healthy male and three healthy female adults as human volunteers, experiments on the head/neck/torso impact responses and the cervical vertebral motions upon lateral inertia impact was conducted. Table 1 shows anthropometric data on human volunteers. The impact loading direction was set vertical (0 deg inclination) against the shoulder on one side (Figure 2). To be more specific, each test subject sat on one side of the impactor, with the back set practically straight against the stiff seat, so that the impact direction become parallel to the line connecting the acromion and the lower part of the cervical vertebrae. In order to analyze the differences in impact loading directions, the impact was also applied from 15 deg forward and 15 deg backward directions (Figure 2), in addition to the 0 deg direction. The impactor surface is rectangular with an area of 100 mm x 150 mm. The impact loading location against the subject's shoulder was set so that the position of acromion would become the same as that of the impactor upper surface. In order to find the difference in effects of neck muscle response on the head/neck/torso motions, the states of muscle were set in tensed and relaxed conditions, respectively. The impact load was set at 3 different levels such as 400 N, 500 N and 600 N in order to find the differences in head/neck responses to the lateral impacts. For the direction with 0 deg inclination, impact responses were compared between cadaver tests and those on the volunteers. Table 2 shows the different test conditions classified

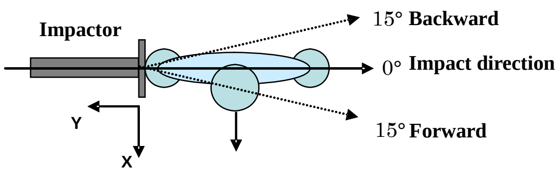

Fig.2 Impact directions

by differences in sex (male and female), impact loading levels, impact directions and states of muscle, with different combinations of test conditions.

Table 2 Test conditions

No. of Subject	Sex	Impact force (N)	Impact direction	Muscle condition
8	Male Female	400	15° forward	Relaxed Tensed
		500	0 degree	
		600	15° backward	

Informed Consent for Volunteers

The informed consent procedure in line with the Helsinki Declaration (WHO/CIOMS, 1988) was conducted in order for the volunteers to be fully informed of the purpose and method of experiments and also to ensure their full consent. The details/contents of the experiments were subjected to the approval of Special Committee of Ethics, Medical Department, Tsukuba University.

ANLYTICAL METHODS

Impact Force Applied to Head/Neck

Head acceleration was measured with the head 9 channel accelerometer, first thoracic vertebra (T1) acceleration was measured with 3-axis accelerometer, and electromyogram was analyzed. The measuring instruments were the head 9ch accelerometer (X, Y & Z), head angular velocity sensor (X, Y & Z), T1 accelerometer (X, Y & Z) and the pelvis accelerometer. The locations where the sensors were attached are shown in Figure 3. A mouth-piece suitable for the teeth profile (teeth impression) was prepared for each test subject. Assuming that the head is rigid, the head coordinate system was set in line with the location of anatomical center of gravity. The 9 channel acceleration measurement method (Ono et al., 1980) was applied according to the

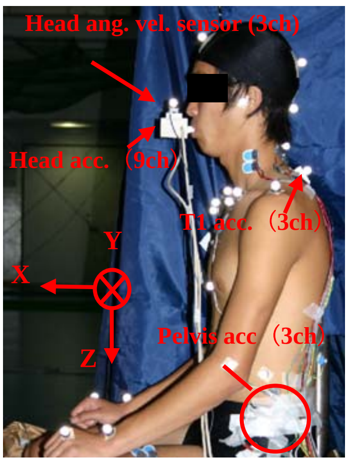

Fig.3 Mounting of accelerometers and rotational velocity sensors

coordinates of each accelerometer in this system, and the rotational and linear accelerations at the head CG were calculated.

Torso Acceleration (T1)

For the measurement of acceleration at T1, a three-axial accelerometer was attached onto the skin over a spinous process of T1.

Three-dimensional Motions of Head/Neck/Torso

The three-dimensional motions of head/neck/torso were measured by means of a VICON Motion Capture. Then the right-shoulder strain (displacement), left-shoulder strain (displacement), head rotation angles (X, Y & Z), T1 rotation angles (X, Y & Z) and the head rotation angles relative to T1 were analyzed.

RESULTS

Characteristic Aspect of Neck Impact Loading & Visual Motions

A 600 N impact loading experiment (in relaxed muscle condition) is shown in Figure 4, with the sequential photographs of the head/neck/torso motions during impact. X-ray of the neck motions under the same test conditions are shown in Figure 5. Figure 6 shows the corridors of the impact forces, the impact velocities, and the impact accelerations of impactor measured in 600 N impact loading experiment (in relaxed muscle condition). The linear and the angular accelerations at the head CG (X, Y & Z) calculated from the values measured with the head 9 channel accelerometer, the accelerations (X, Y & Z) at the T1 are also shown. Figure 7 shows the neck forces (Fx, Fy, Fz, Mx, My & Mz), and the visual head (head displacements and head rotational angles) motions in relation to the T1. Figure 8 shows the visual motions in relation to the shoulder strains (at the sternum upper end and the right or the left acromion) of the right shoulder (right acromion) and the left acromion). On the other hand, the rear view and the lateral views of spine trajectories by the VICON are shown in Figure 9.

Phase 1 [0-50 ms] - The duration of impact for each one of 8 test subjects were 70 ms or so (Figure 6a). The impact load peak levels were fluctuating, as the impactor and the shoulder were not in complete contact in the initial stage of impact. This presumably resulted in the relatively low impact peak level in the initial stage and the relatively high peak level in the secondary stage. The T1 accelerations, on the other hand, showed that the maximum value was found around 50 ms (Figures 6j-6l), while that of the head

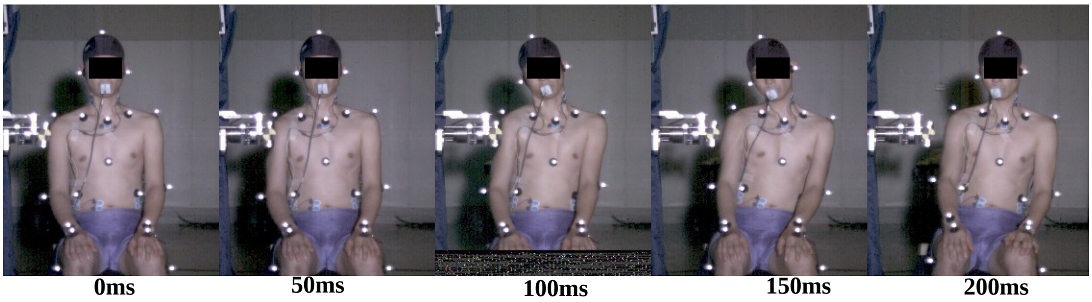

Fig.4 Sequential motions of head/neck/torso (Impact forces: 600N, Relaxed condition)

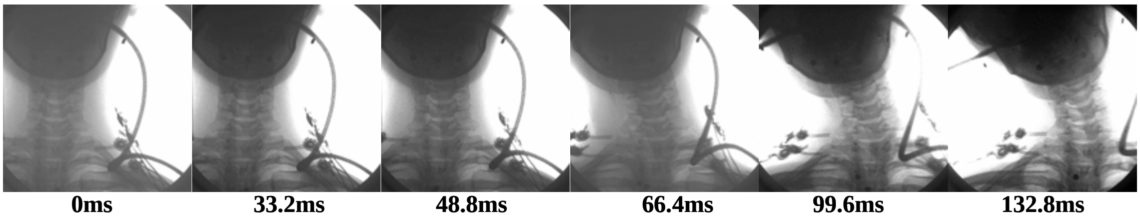

Fig.5 Sequential images of cervical vertebrae by cineradiography (Impact force: 600N, Relaxed condition)

was around 60 ms (Figures 6d-6f). The maximum values of T1 and the head in the Y-axial direction were 55 m/s^2 and 18 m/s^2, respectively. It is deduced that the axial forces between the T1 and the head were acting in opposite direction of compression, as the accelerations of T1 and the head in the Z-axial direction were reversed around 50 ms. The rotations of the head and T1 around the X-axis were reversed around 30 ms. The rotations around the Z-axis were also reversed. The neck shear force (in Y-axial direction) and the neck moments around X-axis and Z-axis did not show their maximum values around 50 ms (Figures 7m), 7q), 7r)), but the axial force of neck in Z-axis showed the maximum value at 50 ms or so. The right shoulder strain (on the impact side) showed the maximum value around 70 ms (Figure 8a). A slight torsion of upper cervical vertebrae was found around the Z-axis (Figure 5).

Phase 2 [50-100 ms] - The impact was continually set up to 70 ms or so (Figure 6a), and the shoulder was separated from the impactor due to the torso inertia. Hence, the acceleration at each portion of the head drops thereafter (Figures 6d-6f). However, the head rotates laterally against the torso, and the acceleration in the X-axial direction starts to increase around 90 ms, as the head is subjected to a restriction by the lateral bending at the same time. The head rotation angles found from the three-dimensional motion analysis by means of VICON Motion Capture showed the maximum values around 100 ms in both X and Z axial directions (Figures 9a-9b). The timing was roughly the same as the timing when the head rotational angle relative to T1 was highest. The maximum value around the X-axis was 32 deg, and 25 deg around the Z-axis. Similar to this trend of head acceleration, the neck shear force decreases around 90 ms, but increases again as the head acceleration was restricted by the lateral bending. The displacements of right and left shoulders and the strains start resuming at the initial states around 80 ms, while the upper cervical vertebral torsion and the lateral extension which occurs mainly at the lower cervical vertebra also started (Figure 5).

Phase 3 [100-300 ms] - The impact loading already stopped, but the entire body keeps rotating clockwise due to inertia. The T1 acceleration in Y-axial direction converged around 150 ms, whereas the head acceleration remains up to 200 ms or so (Figures 6d-6f). The T1 rotation angle around the Y-axis showed gradual changes after 100 ms, while the head keeps on rotating. The lateral extension of cervical vertebrae starts to end, resuming the initial states while maintaining the torsion in the Z-axial direction. It was found from the three-dimensional motion data obtained with VICON that the torsion angle around the Z-axis resumed the initial state at 300 ms or so (Figure 9b). The lateral extension of cervical vertebrae started to resume in the initial state while maintaining the torsion in the Z-axial direction (Figure 5).

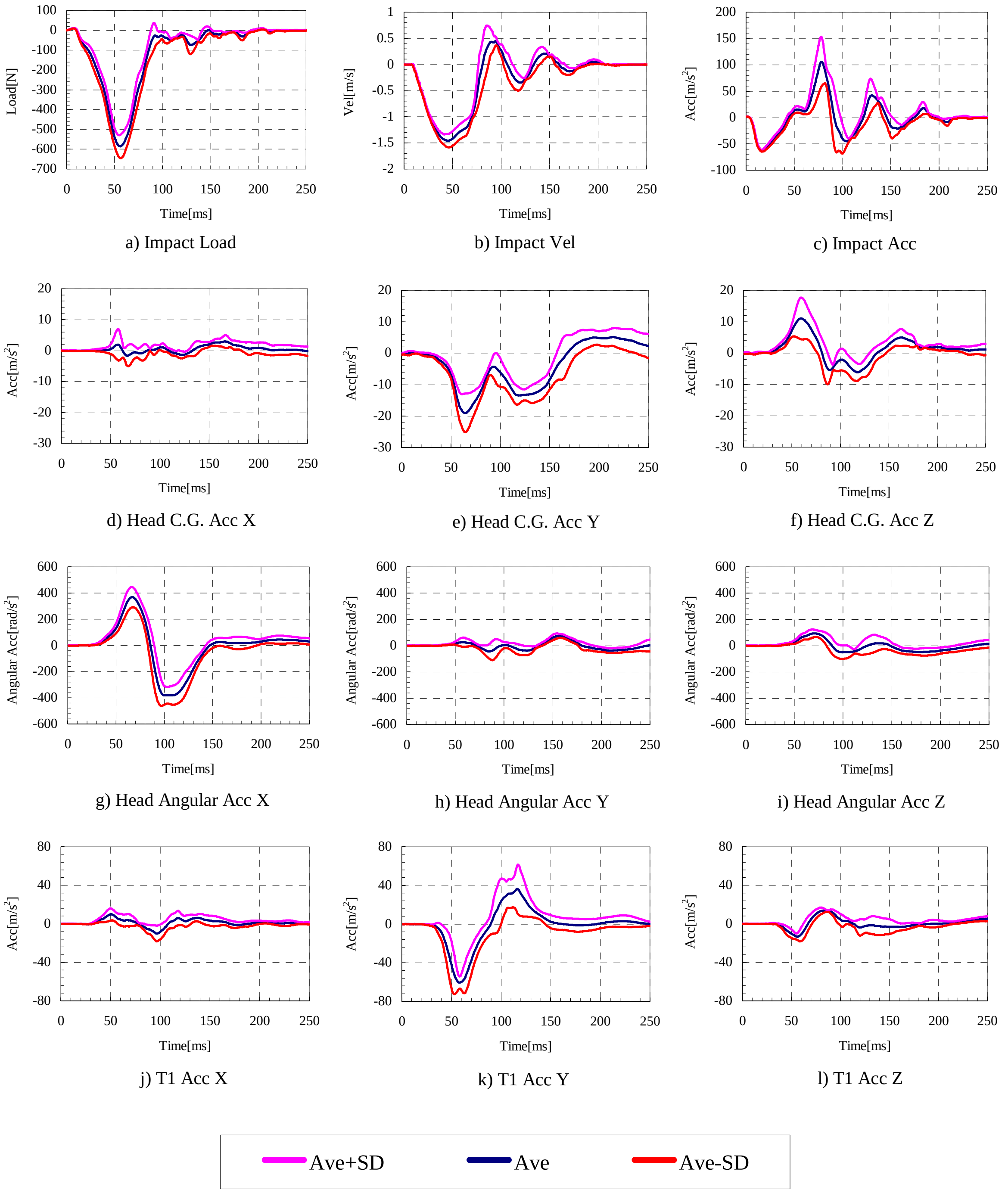

Fig. 6　Impact load, Head C.G. Acc., Head angular Acc., and T1 Acc., (Relax, 600N)

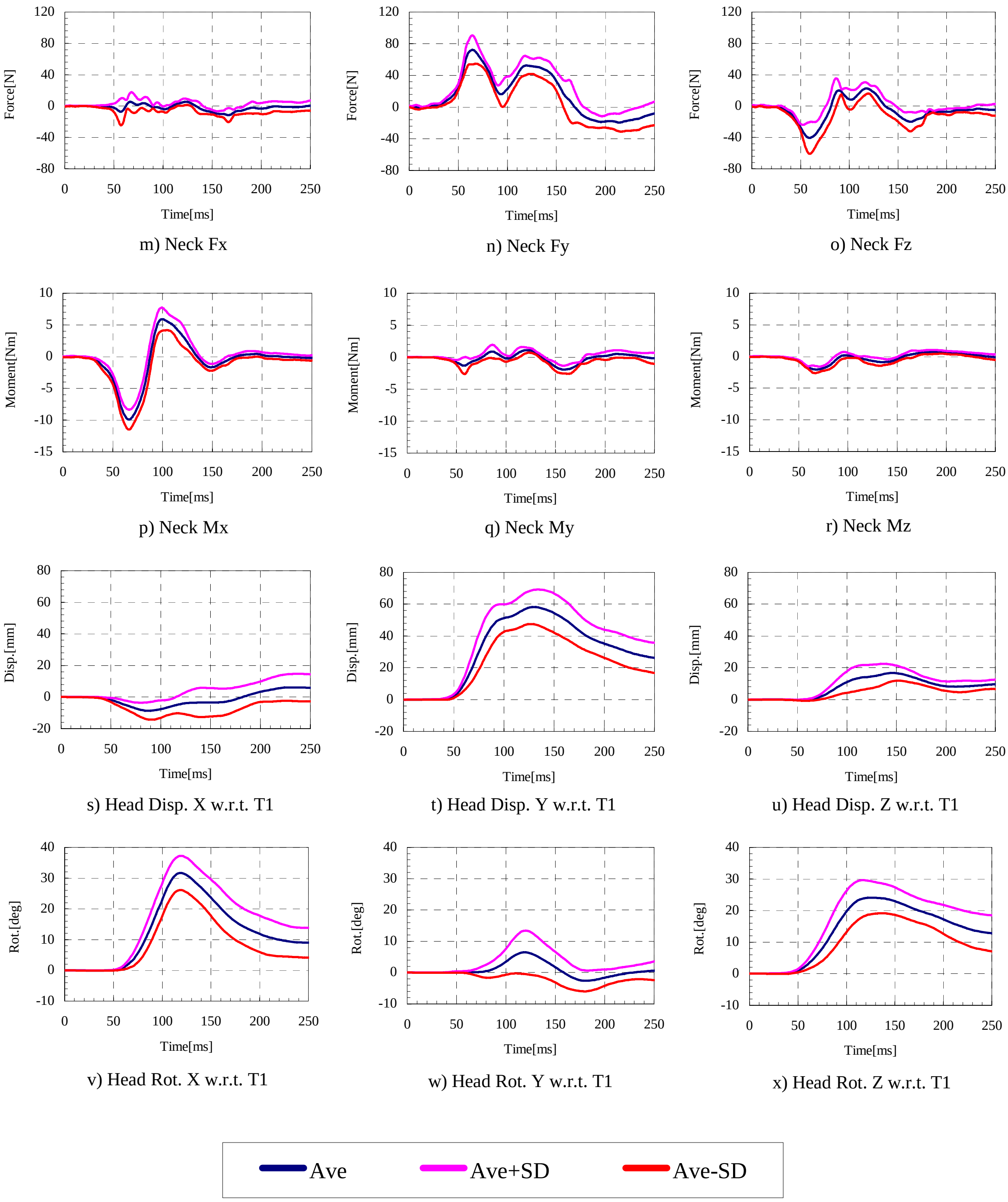

Fig. 7 Neck force, Neck moment, Head Disp. and Rot Ang. w.r.t. T1 (Relax, 600N)

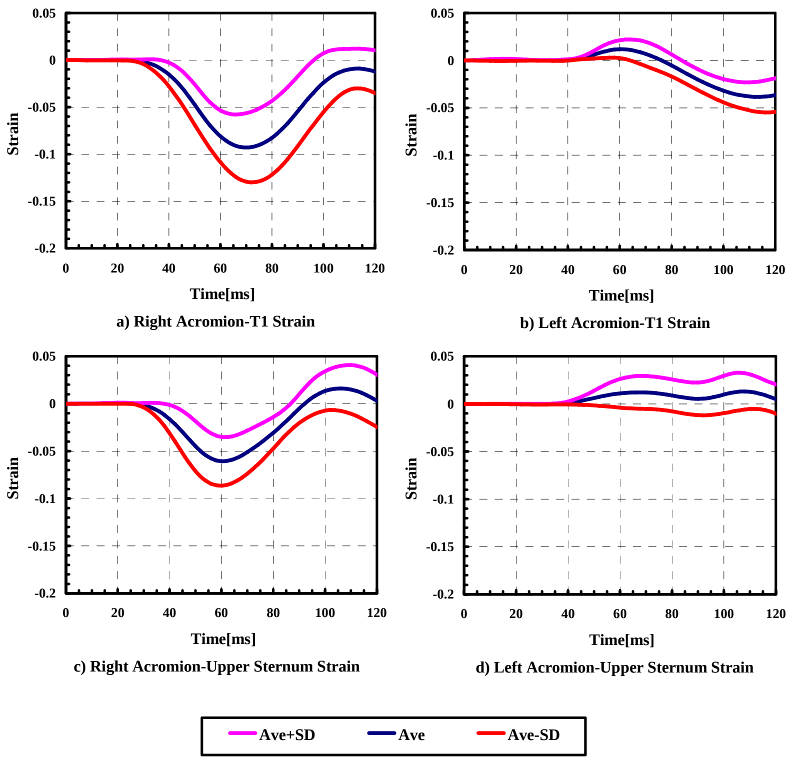

Fig. 8 Shoulder strain at the sternum upper-end and the right or left acromion

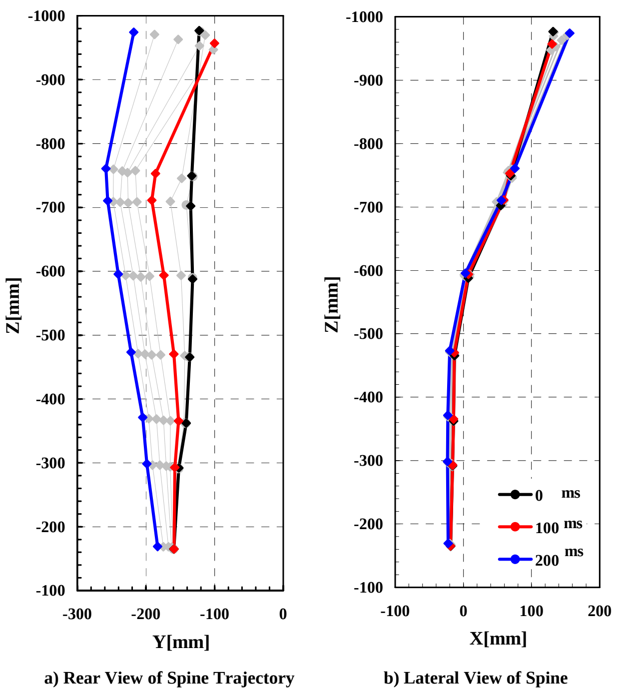

Fig. 9 Views of spine trajectories by the VICON

DISCUSSION

Effect of Differences in Muscle Functions of Head/Neck/Torso Impact Responses

The average value of T1 acceleration for tensed/relaxed muscle conditions with an impact load of 600N is shown in Figure 10. The maximum of T1 acceleration becomes 60m/s^2 in the case of the relaxed muscle condition. On the other hand, the maximum of T1 acceleration becomes 50m/s^2 in the case of tensed muscle condition. Suppression of T1 acceleration under the different muscle conditions was observed. Generally in the case of tensed muscle condition, impact force is transmitted easily to the T1 region when stiffness of the shoulder structure increase. The T1 acceleration rapidly increases according to this phenomenon, and its value becomes greater. Furthermore, effective mass of the shoulder region which was impacted showed higher stiffness. As a result, T1 acceleration decreased and there was an increase in muscle tone, thus, impact force acting on the upper neck is reduced (Fig.11) at an average of 15%. Furthermore, in the case of tensed muscle condition, the motion of head rotation is suppressed so that the stiffness of neck structure itself is increasing (Fig.12 and Fig.13). According to this result, it can be said that the impact motion responses of head/neck/torso easily change based on the different state of muscle conditions.

Effects of Differences between Male & Female on Head/Neck Impact Responses

The maximum of T1 acceleration and head C.G. acceleration under the relaxed muscle condition with impact force of 600N (three males and two females) are shown in Fig.14 and Fig.15. As for the head C.G. acceleration, female subjects showed greater value than male subjects. For the T1 acceleration, no difference was seen between male and female. As a result, even if the force level in lateral impact is

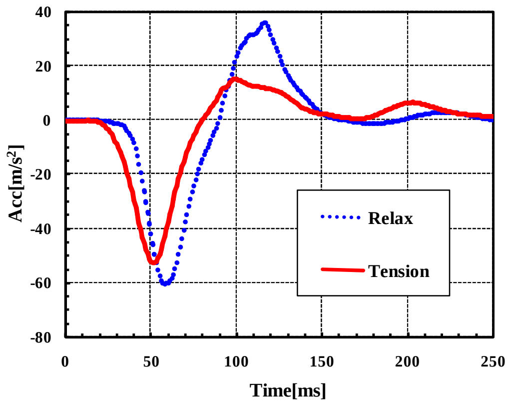

Fig. 10 Comparison of T1 acceleration between relaxed and tensed muscle conditions

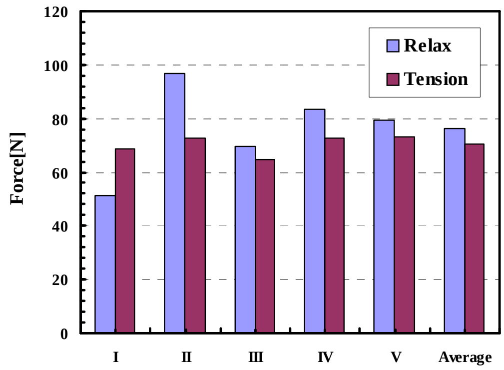

Fig. 11 Comparison of neck shear force (Fy) between relaxed and tensed muscle conditions

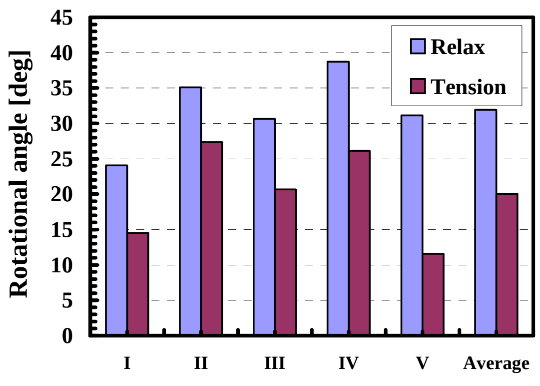

Fig. 12 Comparison of head rot. ang (Y) w.r.t. T1 between relaxed and tensed muscle conditions

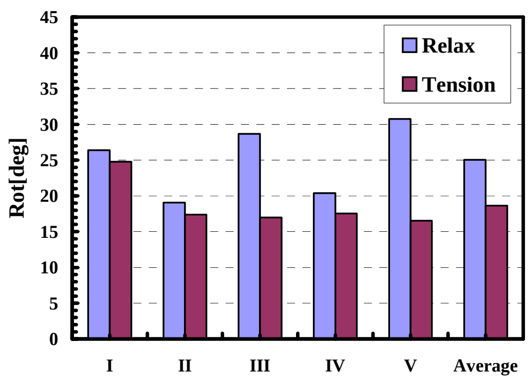

Fig. 13 Comparison of head rot. ang (Z) w.r.t. T1 between relaxed and tensed muscle conditions

almost same, difference of the head/neck motion is observed between male and female. This could probably be due to the smaller head mass of females compared to males. Furthermore, it is thought that the structure size of cervical vertebrae of a female being small might be the cause. The maximum head displacement relative to T1 in the Y-axis and the maximum head rotational angle relative to T1 in the X-axis under the relaxed muscle condition with impact force of 600N are shown in Fig.16 and Fig.17, respectively. The displacement and rotation of head/neck for both male and female were suppressed by doing muscle tone. However, the displacement and the rotation of the head/neck for two female subjects were greater than those of male values under the tensed condition, whereas no difference was observed between male and female under the relaxed condition. According to this situation, it is suggested that under tensed muscle condition, stronger muscular strength of males in general can greatly depress the head/neck/torso motions. On the other hand, females who have weak muscular strength, has difficulty in suppressing the global motion. According to the difference in responses of head/neck/torso between males and females, it is supposed that there will be a higher risk of neck injury for females.

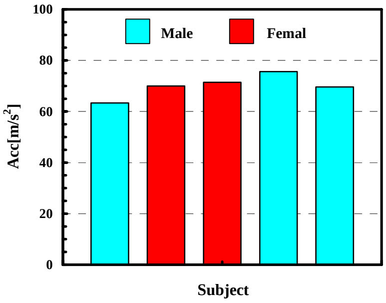

Fig. 14 Max. T1 acc. (Relax, 600N)

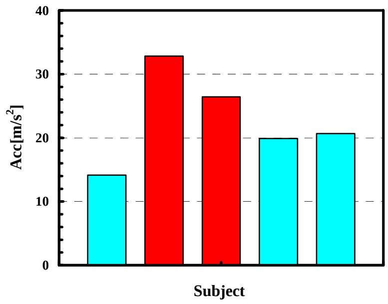

Fig. 15 Head C.G. acc. (Relax, 600N)

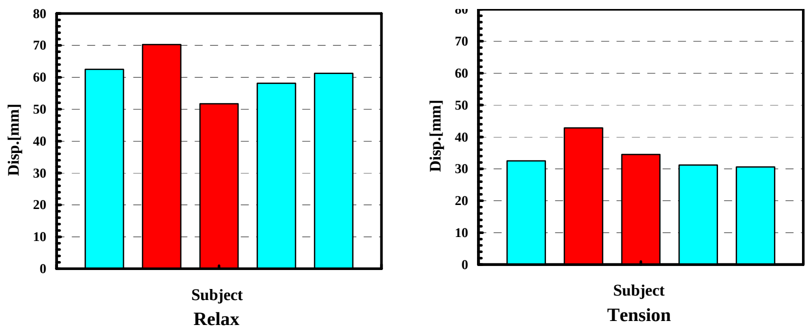

Fig. 16 Head disp. (Y) w.r.t. T1 (600N)

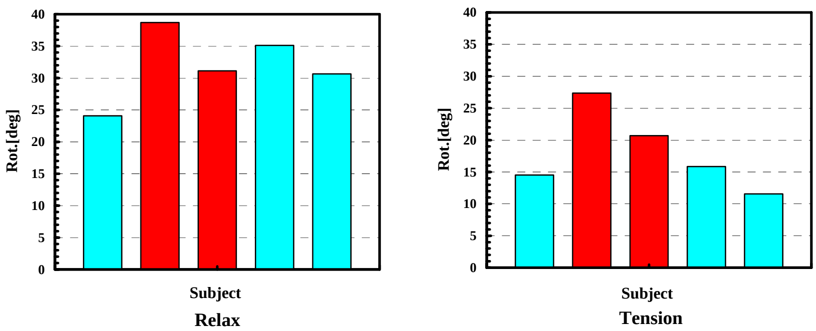

Fig. 17 Head rot. ang. (X) w.r.t. T1 (600N)

Effect of Shoulder Structural Deformation on Head/Neck Impact Responses

Sabine et al (2002, 2003, and 2004) reported that a difference of motion such as the clavicle and the shoulder blade etc. was clarified in the experimental studies on the PMHS lateral shoulder impacts. In the lateral collision, the impact which went from the shoulder takes the influence of the shoulder structure greatly before reaching neck region when an impact acts on the occupant's shoulder region through the vehicle inside structure such as a door panel. And, a change in the impact energy dispersion of the shoulder region, the impact transmission direction of the torso and so on occurs at the same time. The shoulder structure which influences the motion responses of head/neck in the lateral impact was examined here.

When a lateral impact is imposed to the shoulder region, it is transmitted to the clavicle and thorax, the sternum through the shoulder blade, and it influences the neck region consequently through T1 region (Fig.9). The compression strain between the right acromion and the T1 was greater (Fig.8a), Fig.8c)). This corresponds to the result of the PMHS experiment by Sabine et al (2002, 2003, and 2004). It is not compressed comparatively because the clavicle exists between the acromion and the sternum and it is fixed firmly when an impact is imposed from the lateral direction to the shoulder region. The shoulder blade may slide behind the aperture thoracic superior by the impact, and greatly compress in the acromion and the T1. In other words, the acromion and the aperture thoracic superior though an impact is transmitted directly, and the transmission of the impact is delayed in the acromion and the T1. The rising time of the lateral displacement of shoulder markers were shown in Table 3. Displacement between the sternum top-end and the left acromion almost started at the same time, and the motion of T1 was delayed. This shows a difference in the impact transmission mechanism that the neighborhood of the bone structure on the torso front side such as the sternum and clavicle followed by the movement of the neighborhood of the bone structure on the torso rear side such as T1.

Table 3 Rising time of the lateral displacement of the shoulder markers (Relax, 600N)

Subject	Rising Time of Displacement (ms)			
	Right Acromion	Upper Sternum	T1	Left Acromion
I	8	16	26	14
II	8	28	30	22
III	8	18	22	16
IV	10	14	28	22
V	8	20	28	20
Average	8.4	19.2	26.8	18.8

It is understood that the different motion response was due to the structural difference of the rear and front torso as described above. An impact was introduced to the left acromion directly without deformation between the left acromion and the sternum top-end though the impact transmitted to the top-end of the sternum was transmitted to the left acromion through the clavicle on the opposite impact side. In other words, the left acromion was imposed an impact through the top-end of the sternum, and the left acromion was displaced backward. It can be considered that the strain of the left acromion and T1 showed slight tension at first, and as a result showed compression.

Characteristics of Cervical Vertebral Motions during Lateral Impacts

The head rotation was delayed for about 30ms to the neck, after which, head rotation begins. The rotation of C4 was lower than that of C5 in 35-80ms (Fig.18). It can be considered that the torso moves first, and then the left lateral moment acts to the upper neck as shown in Fig.19. Furthermore, C4/C5 which is the relative rotational motion of cervical vertebrae as shown in the Fig.20 showed a negative value in the early stage of impact. This indicated that the tension of the left cervical vertebral joint in C4/C5 and the compression of the right cervical vertebral joint in C4/C5 occurred. It was estimated that the rotational angle of C1～C3 which can not be analyzed in this experiment will be delayed from that of the lower cervical vertebra, and the rotational angle of the upper cervical vertebra will exceed that of the lower cervical vertebra. The rotation angle of C5 suppressed those of the head and C4, showing that the cervical spine has a bi-phases curvature form such as an S-curve. An S-shape form with relative left extension of upper cervical vertebra and relative right flexion of lower cervical vertebra was presented concretely, and it can be considered that the right bending moment was acting on upper cervical vertebra and the left bending moment was also acting on the lower cervical vertebra. This phenomenon shows the same type of cervical vertebral motions causing the whiplash during a rear-end collision.

Moreover, tension on the left side of the cervical vertebra always shows an increase tendency as shown in Fig.21. On the other hand, compression on the right side of the cervical vertebra (C4/C5～C7/T1 in 90-120ms) shows a constant value (Fig.22). The rotation angle of the cervical vertebra was depressed by restricted motion of the facet joint on the right of cervical vertebra, and it can be considered that larger compression acts on this area at the latter half of impact. The compression of the intervertebral disk decreased with the elasticity of the neck itself due to a decrease in compression and the axial force applied on the upper neck shifted to tension force after 130ms (Fig.23).

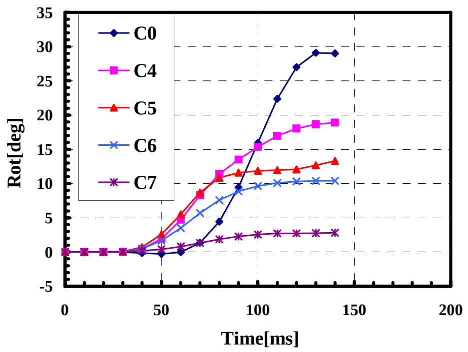

Fig. 18 Vertebral angle w.r.t. T1

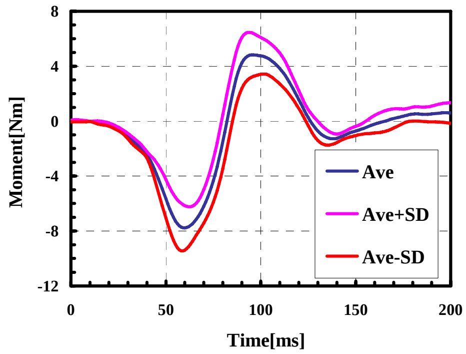

Fig. 19 Neck Moment

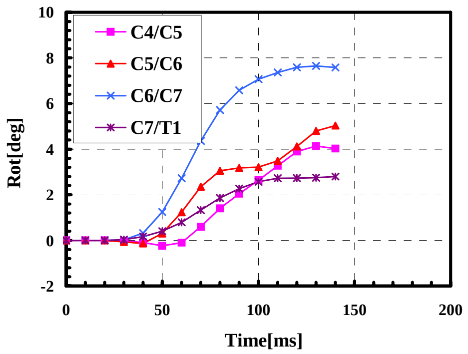

Fig. 20 Vertebral angle w.r.t. lower vertebra

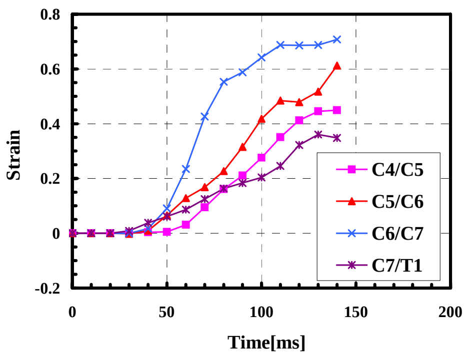

Fig. 21 Left side strain of intervertebral disc

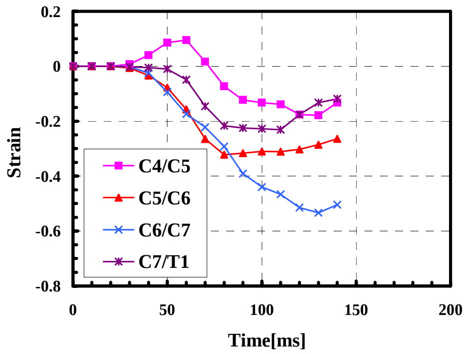

Fig. 22 Right side strain of intervertebral disc

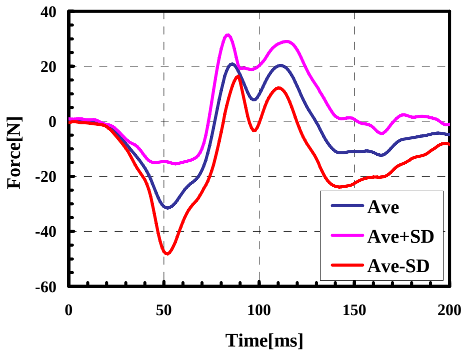

Fig. 23 Neck force Z

CONCLUSIONS

Using five healthy male and three healthy female adults as human volunteers, experiments on the head/neck/torso impact responses and the cervical vertebral motions upon lateral inertia impact have been conducted, with the impact forces set at 400 N, 500 N and 600 N, respectively. The findings obtained from the above are as follows:

Effect of Differences in Muscle Functions of Head/Neck/Torso Impact Responses

The suppression of head/neck/torso motions was greater in tensed muscle than in relaxed condition. The T1 displacement (18%) and the head displacement (48%) relative to T1 were more suppressed in the tensed condition than in relaxed condition.

Effects of Differences between Male & Female on Head/Neck Impact Responses

Regardless of the state of muscle tension, the displacement of acromion with respect to the first thoracic vertebra (T1) tends to be greater for male than for female subjects. As female shoulders tend to have less flexibility against impact than male, the female cervical vertebral motions are likely to show longer lateral extensions than male. It is suggested that the differences in muscle responses should be taken into account, in addition to the differences in shoulder anatomical structures, as marked differences between male and female.

Effect of Shoulder Structural Deformation on Head/Neck Impact Responses

When an impact is applied to a shoulder, the head/neck/neck impact responses become different even if the magnitude of impact on the torso is the same. Thus, it is suggested that the differences in head/neck/torso motions are caused by the differences in shoulder anatomical shape and/or front-rear structural differences. A shoulder has high three-dimensional flexibility and a wide range of movability, owing to the gleno-humeral and sternoclavicular joints, which facilitate vertical and lateral motions against lateral impacts. However, the shoulder movability would be restricted, if the direction of the lateral impact roughly aligns with the line connecting the acromio-clavicular joint and the sternoclavicular joint - i.e., the longitudinal direction of the clavicle.

Characteristics of Cervical Vertebral Motions during Lateral Impacts

Cervical vertebral rotations all started at 35 ms, but the time required to reach the peak rotation increased toward the upper vertebrae, with C7 and T1 peaking at 120 ms and the final peak in the head at 120 ms. At around 35-80 ms, the rotation angle of C5 surpassed those of the head and C4 showing that the cervical spine was bending into an S-curve. This phenomenon shows the same type of cervical vertebral motions causing whiplash during a rear-end collisions. Also, extreme compression was at work in the vertebral disc and/or the facet joint in C6/C7 and C7/T1, suggesting a high probability of injury occurring in the neck.

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