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X-Ray Study of the Human Neck Motion Due to Head Inertia Loading

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ABSTRACT

This study presents results from x-ray analysis of live human head/neck motion in sled test simulations of low-speed frontal, lateral, and rear-end vehicle impacts. The test subjects were 26 male and female adults, aged 22 to 61 years. Head/neck motion and the kinematic responses of each test subject were measured and analyzed by cineradiograph, high-speed film, accelerometers, and electromyography of the neck muscles.

The methodology used may provide insight into the mechanism of neck injuries caused by the head inertia loading. The actual kinematic responses of the head/neck were found to be more complex than previously thought. The experimental results suggest that the most significant factor of the head/neck response is the initial curvature of the cervical and thoracic spine. Looking specifically at the early motion of the head and neck in rear-end impacts, the cervical forward curvature (lordosis) and the thoracic rearward curvature (kyphosis) were found to straighten. In the leaning-forward or stooped-shoulder posture, the cervical spine was affected by compression load resulting from upward movement of the upper thoracic spine, and it appears that the cervical spine length was shortened. In all tests, the flexion and extension motions measured were never beyoned the physiological range.

INTRODUCTION

The best definition of neck response to date is from the work of Mertz and Patrick (1967, 1971) based on human volunteer tests and on cadaver tests. The tests of particular interest are those comparing subjects with relaxed and tensed neck muscles. There have been little other human experimental data, since any experiments with volunteers must necessarily stop short of actual injury levels.

Neck injuries are generally classified as cervical hyperextension or hyperflexion (whiplash) injury. However, it should be noted that complaints of neck injury are frequent in cases without cervical hyperextension or hyperflexion. These include symptoms such as localized neck pain, pain radiating to the shoulders, vague aches, discomfort, and vertigo. The mechanism of these neck injuries from low-speed collisions is still undefined, and the relative angular movement between the head and thorax, appears to be a poor indicator of injury.

In this study cineradiography was used with volunteer test subjects to study the range of motioin of the cervical spine, and vertebrae translation and angulation in the sagittal plane for velocities from 2.5 to 5.8 kph. The test runs included 19 rear-end impacts, 4 frontal impacts, and 3 lateral impacts. In rear-end impacts, one test run employed a crash dummy (Ito Seiki 3DGM-JM50). The safety and security of test subjects during and after the test run were discussed and evaluated by a joint research committee comprised

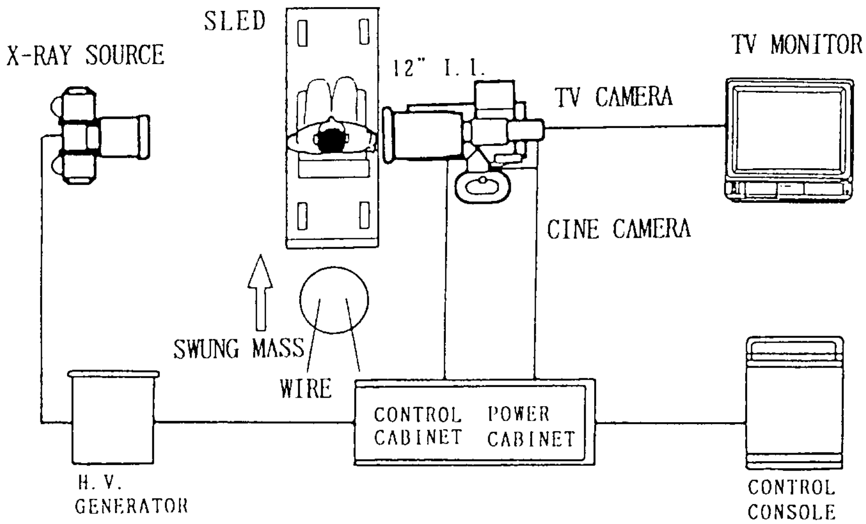

Figure 1. Block Diagram of Cineradiogragh Equipment

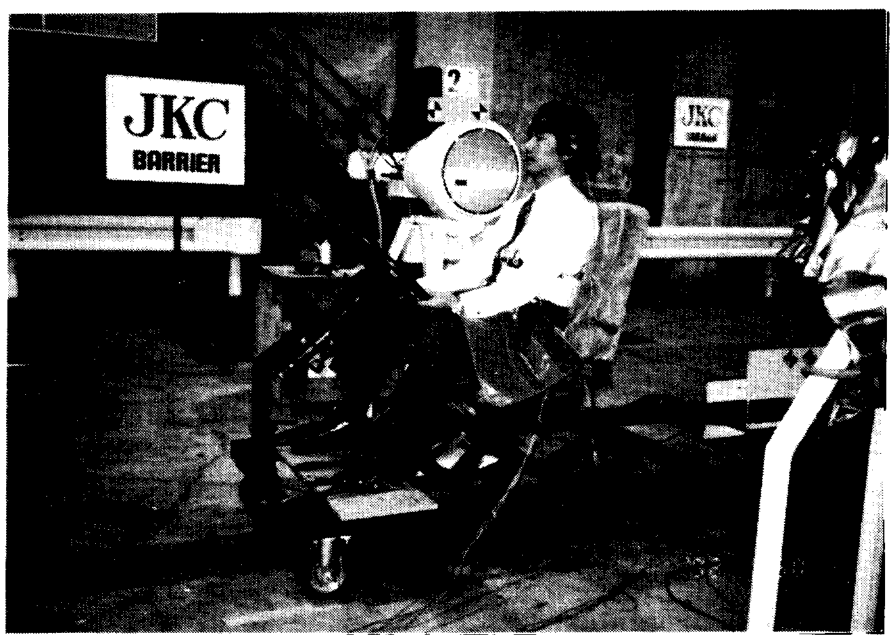

Figure 2. Photograph of Subject Readied for Rear Impact Test

of medical doctors, lawyers, engineers, etc. Informed consent of the test subjects complied with the contents of the Declaration of Helsinki (18th World Medical Assembly 1964).

METHODS

IMPACT FACILITY—To provide controlled impacts in the low-speed range, a pendulum style impact facility and sled were designed and fabricated. The test facility is located indoors at The Motor Insurance Repair Research and Training Center Ltd. The facility is capable of impact speeds up to 15 kph with a swung mass of 150 kgf. The sled shown in Figure 2 is 2.5 m long by 0.8 m wide, and weights about 100 kgf. The sled was accelerated by impact of a swung mass. Urethane foam padding was installed on the face of the swung mass and the impact surface of the sled to simulate the front and rear end of a vehicle. The resulting velocity change(ΔV) of the sled due to impact was accurately measured by a high-speed video system. Three automotive seats with head restraints and different seatback stiffnesses (a 1991 Honda Today, a 1988 Toyota Crown, and a 1991 Nissan Pulsar) were selected for testing. The test seat was mounted on the sled so that the height of the x-ray image intensifier was aligned with the subject's neck.

CINERADIOGRAPHIC EQUIPMENT– The cineradiography (Toshiba Medical KXO-1250 Generator and an ARRI TECHNO 35 Cinecamera) equipped with a 12-in-diameter image intensifier was used to record lateral images of the skull and the cervical vertebrae onto cinefilm. The radiation exposure rate for this unit was 4 mA over one second at an intensity of 125 kVp. The cineradiograph was filmed at 90 frames per second.

TEST SUBJECTS–Test subjects were 22 male and 4 female healthy volunteers, ranging in age from 22 to 61 years. All test subjects were informed about the test procedures and risks and signed a consent form approved by the joint research committee. Each subject also completed pretest physical evaluation including radiographic imaging and MRI (Magnetic Resonance Imaging) studies of the neck. Each subject performed one test run, and each subject's genital area was covered with a lead shield during the test run and cineradiography.

INSTRUMENTATION– High-speed cameras and a video camera synchronized with the cineradiography recorded subject response at 200 frames per second, and provided a close-up lateral view of the test subject. Accelerometers (Kyowa AS-20HB) were mounted on the sled frame to measure G_x (forward/rearward) motion, and on the frontal and temporal surfaces of the head to measure G_x and G_z (upward/downward) motions, on the front surface of the chest, and on the upper surface of the thigh to measure G_x motion. Surface EMG electrodes were attached to the skin over the trapezius, sternocleidomastoid, and infrahyoid muscles, to measure muscle reflex time, and analyze the activation of the neck muscles.

HEAD/NECK MOTION ANALYSIS – On the sequential radiographs, the shape of the cervical spine, the configuration and orientation of each vertebra were traced using a film motion analyzer (NAC PH-160F). The changes in position of each vertebra from one radiograph to the next were plotted. The excursion of the whole motion of the upper cervical vertebrae (C1/C2) relative to the lower cervical vertebrae (C6/C7) of each test subject was measured by superimposing respectively the traced results. These ranges of motion were compared with the voluntary ranges of motion determined by the still head /neck radiographs taken in full neck flexion and full neck extension.

RESULTS

ACCELERATION– Figure 3 shows typical acceleration responses of the sled and subject. In rear-end test for a ΔV of 4.7 kph, the sled peak acceleration was about 7.6 G for about 40 ms and the total sled acceleration lasted about 55 ms. Compared to a representative vehicle, this sled acceleration pulse is rapid and short, similar to that of vehicles with a stiff frame like trucks and compact cars. These results were due to the limited deformation of the sled impact face. Also, the acceleration was influenced by the subject's mass at about 50 ms after the impact.

The thigh acceleration generally peaked at 3.5 G at about 70 ms after the impact, and then decayed to below zero at 155 ms. The chest acceleration peaked at 3.4 G at about 80 ms, and then decayed to below zero at 170 ms. The head acceleration remained zero until 100 ms after the impact. It then peaked at 5.8 G at about 170 ms, decaying linearly to below zero at 225 ms.

By comparison, Figure 4 shows responses for the sled and subject for a frontal impact ΔV= 5.7 kph (Runs 21 and 23). The thigh acceleration peaks at 4.5 G at about 50 ms after the impact, and then decays linearly to 0 G at 135 ms. The chest acceleration peaks at 3.2 G at about 75 ms, then decays linearly to 0 G at 190 ms. The head acceleration pulses are significantly different for the unbelted and lap-shoulder belted subjects.

In the case of frontal impacts with lap-shoulder belt, the head acceleration peaks at 4.5 G at about 185 ms after the impact, but in the unbelted case, the head acceleration pulse shows almost no acceleration.

KINEMATIC RESPONSE OF CERVICAL SPINE

Rear-End Impacts– Figure 5 shows a cineradiograph sequence (Run 15) of the head/neck motion for a sled ΔV of 4.7 kph to rear-end impact, the head/neck motion is explaned as follows.

The First Half of Motion – The subject's skull remained almost stationary for about 90 ms after the impact as the chest and shoulders were accelerated by the seatback so that the stooped-shoulder posture became more upright.

The Second Half of Motion –After about 90 ms, the lower cervical vertebrae had begun moving forward and upward, so that the cervical spine was bent rearward by the inertia of the stationary head. This neck extension stopped when the head restraint cushion was sufficiently compressed by

Table 1. Test Series

Run No.	Δ V (kph)	Seat* Type	Sex	Age	Initial Posture	Initial Neck Muscle Tension	Impact Direction
1	4.7	T	Dummy	——	Neutral	———	Rear-End
2	2.5	T	Female	57	Rotation	Relaxed	Rear-End
3	2.7	T	Male	60	Neutral	Relaxed	Rear-End
4	3.5	T	Male	24	Rotation	Relaxed	Rear-End
5	3.6	T	Female	41	Neutral	Relaxed	Rear-End
6	3.6	C	Male	59	Neutral	Relaxed	Rear-End
7	3.6	T	Male	45	Neutral	Relaxed	Rear-End
8	3.6	T	Male	46	Neutral	Relaxed	Rear-End
9	3.6	T	Male	33	Lateral Bend.	Relaxed	Rear-End
10	3.7	C	Male	61	Neutral	Relaxed	Rear-End
11	4.2	C	Female	24	Neutral	Relaxed	Rear-End
12	4.4	C	Male	41	Neutral	Tensed	Rear-End
13	4.7	T	Male	33	Rotation	Relaxed	Rear-End
14	4.7	P	Male	38	Rotation	Tensed	Rear-End
15	4.7	P	Male	23	Neutral	Tensed	Rear-End
16	5.0	T	Male	23	Neutral	Relaxed	Rear-End
17	4.2	C	Male	45	Forward Lean.	Relaxed	Rear-End
18	4.5	P	Male	22	Forward Lean.	Tensed	Rear-End
19	4.8	T	Male	35	Forward Lean.	Relaxed	Rear-End
20	4.9	C	Male	39	Rotation	Relaxed	Rear-End
21	5.7	P	Male	51	Unbelted	Tensed	Frontal
22	5.7	P	Male	22	Unbelted	Tensed	Frontal
23	5.7	P	Male	22	Belted	Tensed	Frontal
24	5.8	P	Male	37	Belted	Tensed	Frontal
25	3.4	P	Male	48	Unbelted	Relaxed	Lateral
26	3.4	P	Female	39	Belted	Relaxed	Lateral
27	4.2	P	Male	39	Belted	Relaxed	Lateral

*T = 1991 Honda Today, C = 1988 Toyota Crown
P = 1991 Nissan Pulsar

the head so that the head began thrusting forward.

Motion of the complete cervical spine measured by superimposing results of sequential radiographs showed all excursions to be within voluntary range of motion. Hyperextension did not occur on any test. Analysis of the first half of head motion showed that the cervical spine went into flexion prior to extension (See Figure 7), and the length of the cervical spine was shortened (See Figure 9).

Kinematic response of head/neck to rear-end impact is illustrated in Figure 12. This illustrates the G_x (forward/rearward) and G_z (upward/downward) accelerations of both the head and chest, the initial inclination of C6 from the horizontal, the angular displacement of C6, and the vertical displacements of both C2 and C6 during the forward 15 cm movement of the shoulders. Test results are summarized in Table 2. Missing data are noted by empty cells ('—'). The initial inclination(ϕ) of

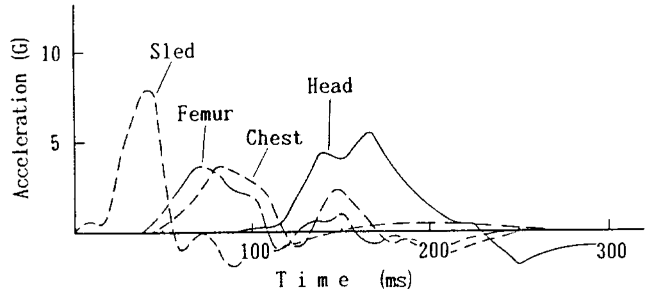

Figure 3. Acceleration—Time Histories of Sled and Test Subject to Rear-End Impact(Run 15)

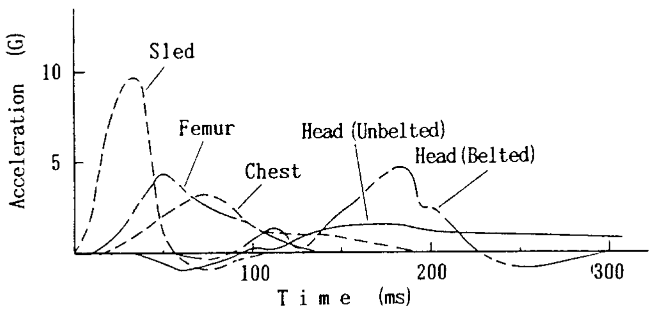

Figure 4. Acceleration—Time Histories of Sled and Test Subject to Frontal Impact(Run 21, 23)

the test subject's C6 vertebra from the horizontal was more than + 10 degrees, but the initial inclination of the dummy's lower neck was - 20 degrees because the dummy's spine is straight and without the lordosis and kyphosis of the human spine.

The motion of the cervical spine was distributed both downward and upward. The large upward displacement of the cervical spine corresponded with the large initial inclination of C6 (See Figure13). In 11 of the test runs (58 %), the lower cervical spine moved upward, while in 8 of the test runs the lower cervical spine moved downward or horizontal. In 8 of the test runs (47 %), the upper cervical spine moved only in extension, while in 9 of the test runs, both flextion and extension were observed (See Tables 3 and 4).

Frontal Impacts—Figures 14 and 16 show typical traced results of sequential radiograghs of Runs 21 and 23 for a sled ΔV of 5.7 kph to frontal impact. Whole motion of the cervical spine measured by superimposing results of the sequntial radiographs showed all movements to be within voluntary range of motion. Hyperflexion did not occur in any test (See Figures 15 and 17).

There was a remarkable difference between the motion of the cervical spine in the unbelted and

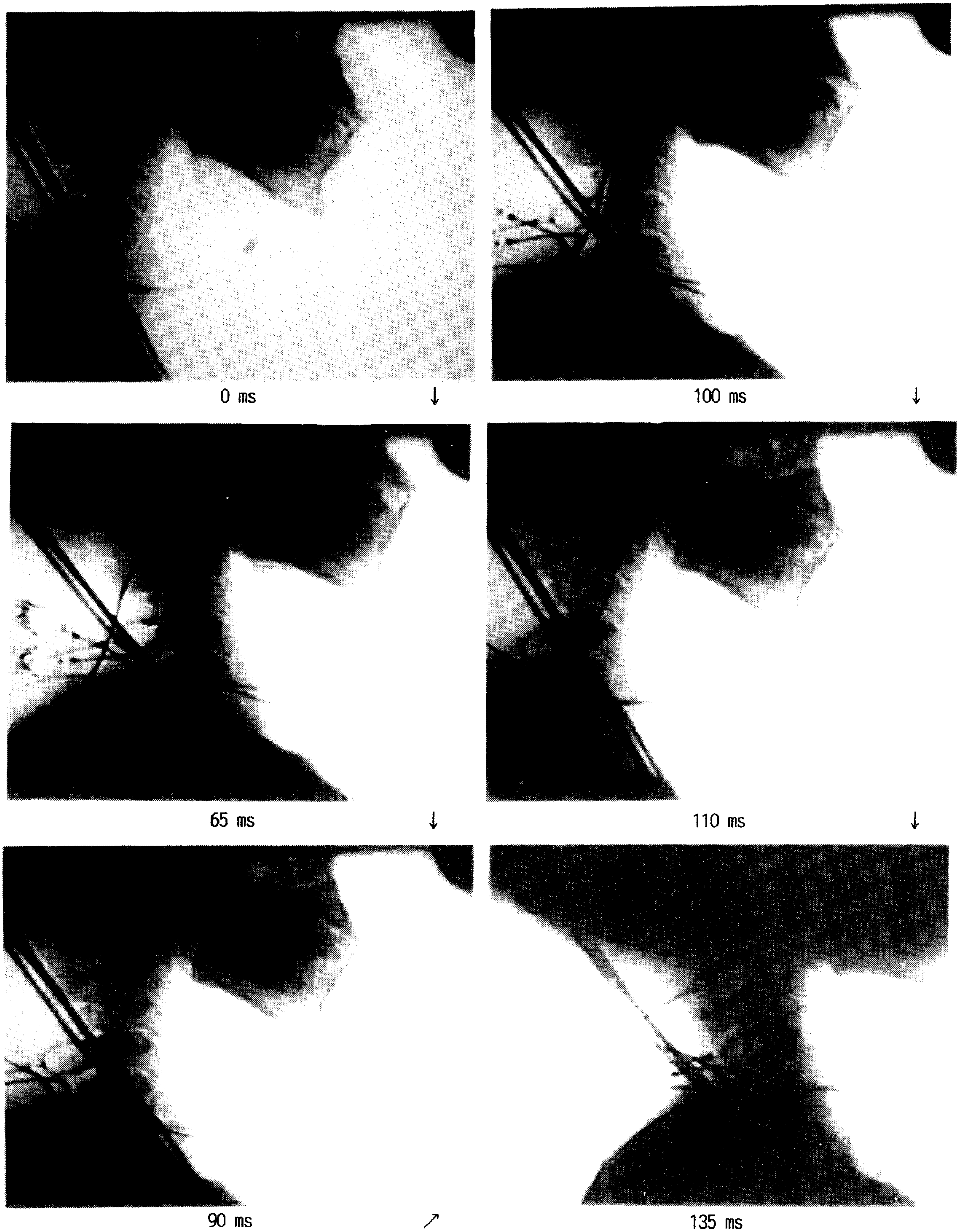

Figure 5. Sequential View of of Cervical Spine Response to Rear-End Impact(Run 15)

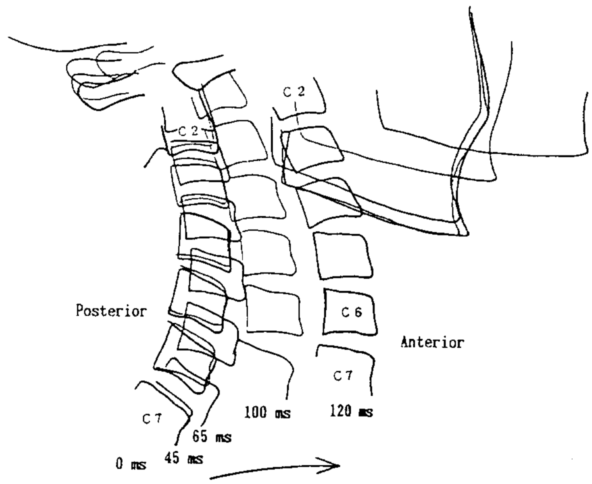

Figure 6. Traced Result of Cervical Motion in Stooped-Shoulder Posture(Run 8)

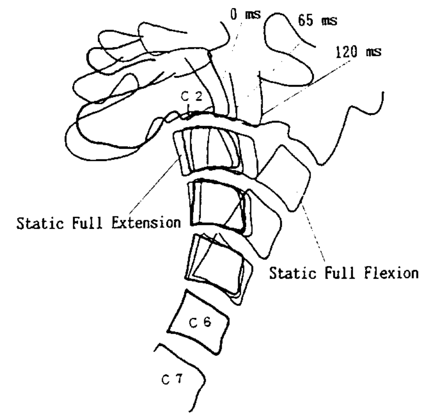

Figure 7. Superimposed Result of Cervical Motion with Voluntary Full Extension and Flexion(Run 8)

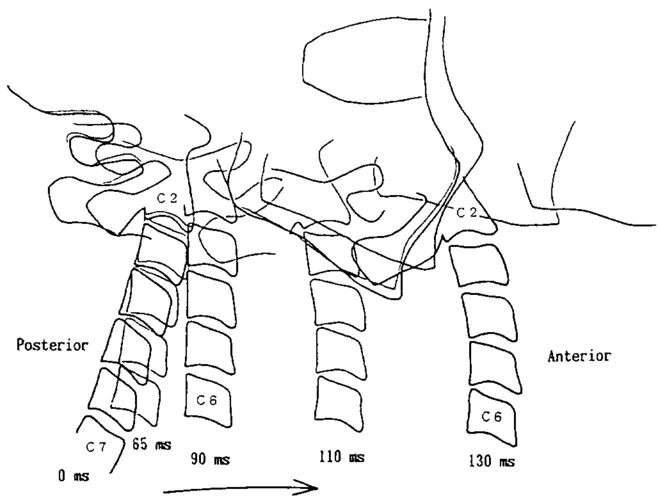

Figure 8. Traced Result of Cervical Motion in Stooped-Shoulder Posture(Run 15)

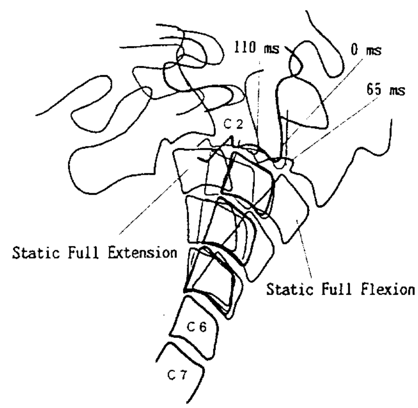

Figure 9. Superimposed Result of Cervical Motion with Voluntary Full Extension and Flexion(Run 15)

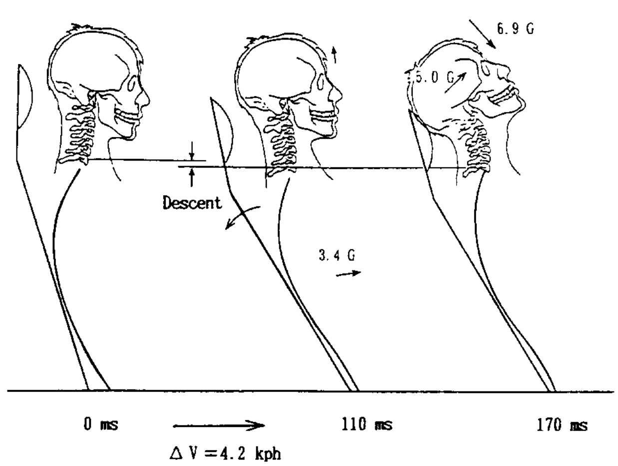

Figure 10. Head/Neck/Torso Responses in Upright Posture(Run 11)

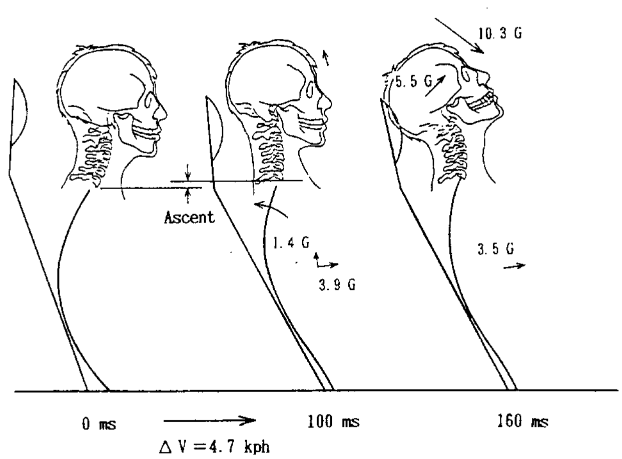

Figure 11. Head/Neck/Torso Responses in Stooped-Shoulder Posture(Run 15)

Table 2. Acceleration and Displacement Results in Rear-End Impacts

Run No.	Δ V (kph)	Chest Accel.(G)		Head Accel. β_{max}(G)	Lower Cervical Displ.			Upper Cervical Displ. u(mm)	Neck Motion	Initial Posture
		α_{max}	γ_{max}		φ (deg)	θ (deg)	d(mm)			
1	4.7	5.1	-1.2	4.8	-20	6	-12	-11	Extension	Dummy
2	2.5	—	—	2.8	21	6	0	0	Flex. & Exten.	Rotation
3	2.7	1.5	0	4.3	23	5	0	3	Extension	Neutral
4	3.5	—	—	——	16	12	- 4	- 4	————	Rotation
5	3.6	—	—	3.5	18	8	3	3	Extension	Neutral
6	3.6	2.3	1.0	3.2	40	13	3	5	Exten. & Flex.	Neutral
7	3.6	2.3	-1.7	5.1	21	7	-10	-10	Extension	Neutral
8	3.6	2.3	2.2	5.4	30	22	19	17	Flexion	Neutral
9	3.6	2.1	-1.6	5.0	10	2	- 4	- 4	————	Lateral Bend.
10	3.7	1.8	0.7	2.7	18	0	5	5	Flex. & Exten.	Neutral
11	4.2	3.2	-1.4	5.5	16	4	-13	-13	Extension	Neutral
12	4.4	3.6	-1.4	6.3	22	10	- 9	-13	Extension	Neutral
13	4.7	—	—	——	24	15	5	7	Flex. & Exten.	Rotation
14	4.7	3.2	−2.4	4.1	17	18	6	5	Extension	Rotation
15	4.7	3.4	1.5	5.8	30	15	2	2	Flex. & Exten.	Neutral
16	5.0	6.2	0.7	6.0	13	6	8	7	Flex. & Exten.	Neutral
17	4.2	4.0	3.3	2.8	56	24	18	20	Flex. & Exten.	Forward lean.
18	4.5	2.4	3.5	2.9	55	11	25	28	Flex. & Exten.	Forward lean.
19	4.8	4.0	2.5	1.4	47	23	28	25	Extension	Forward lean.

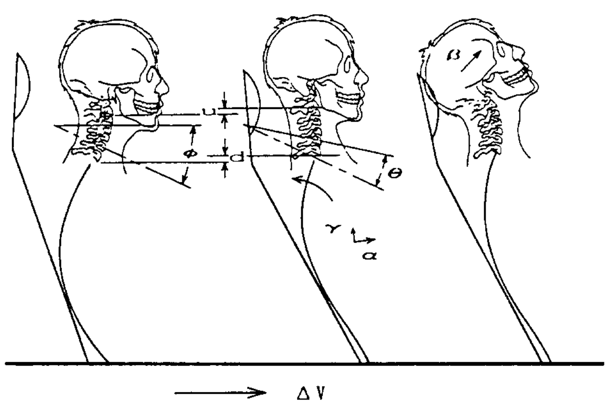

Figure 12. Schematic Representation of Cervical Motion for Rear Impact Test

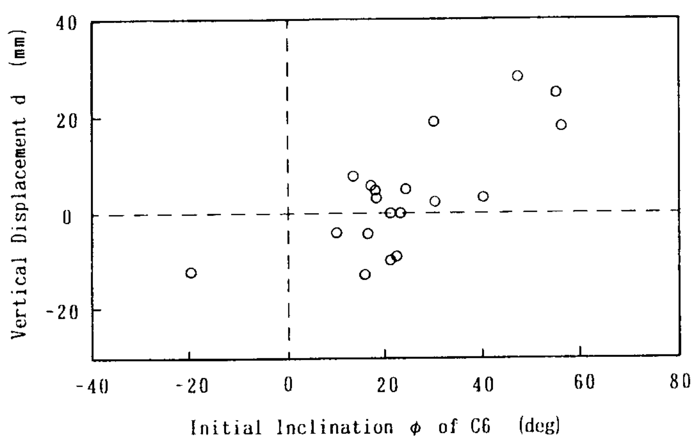

Figure 13. Plot of Vertical Displacement for Initial Inclination of C6

Table 3. Distribution of Vertical Movement

Movement of Cervical Spine	Number	Percentage
Descent	6	32
Horizontal	2	10
Ascent	11	58
Total	19	100

Table 4. Distribution of Extension and Flexion

Motion of Cervical Spine	Number	Percentage
Only Extension	8	47
Flex. and Exten.	9	53
Total	17	100

lap-shoulder belted tests. In lap-shoulder belted tests, the subjects'jaw was forced to protrude due to acceleration of the torso. In the unbelted tests, the shape of the cervical spine remained almost unchanged because there was no acceleration of the torso.

Lateral Impacts — Severe lateral flexion of the cervical spine did not occur during any test runs. Since there was no side structure to restrict the torso, the upper torso was free to rotate toward the impact, minimizing the acceleration required to move the head.

DISCUSSION

On the sequences of kinematic response of the cervical spine due to head inertia loading, the first half of motion was both the rotation and translation of the lower cervical spine. The initial inclination of the lower cervical vertebrae from the horizontal was large when the subject was in the leaning-forward or stooped-shoulder posture. In this posture, the upper torso is away from the seatback surface, as is the case when a driver hunches over the steering wheel, and the cervical lordosis and thoracic kyphosis are conspicuous. In rear-end collisions, when the torso was pushed forward by the seatback, the stooped-shoulder posture became more upright, and the cervical forward curvature and the thoracic rearward curvature were straightened.

The motion of the cervical spine included both downward and upward movement. In the initial posture of leaning-forward or stooped-shoulder, when the torso was rapidly thrust forward by the seatback, a resultant upward axial acceleration was generated at the base of the cervical spine. In the upright or reclined posture, the chest and shoulders descended with rearward deflection of the seatback.

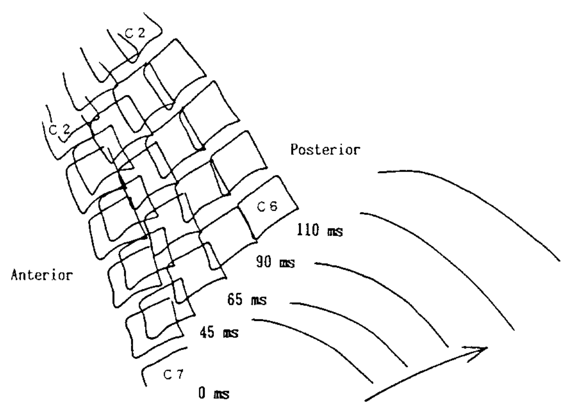

Figure 14. Traced Result of Cervical Motion for Unbelted Subject in Frontal Impact(Run 21)

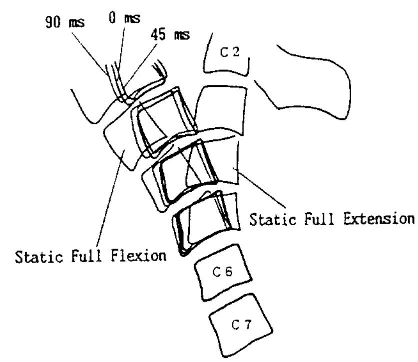

Figure 15. Superimposed Result of Cervical Motion in Frontal Impact(Run 21)

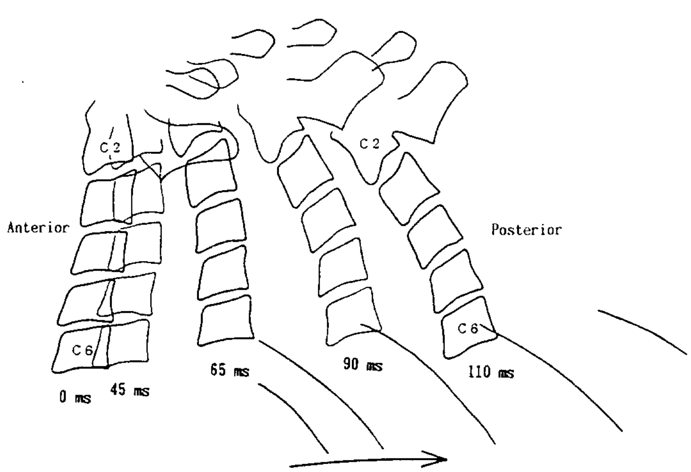

Figure 16. Traced Result of Cervical Motion for Shoulder-Belted Subject in Frontal Impact(Run 23)

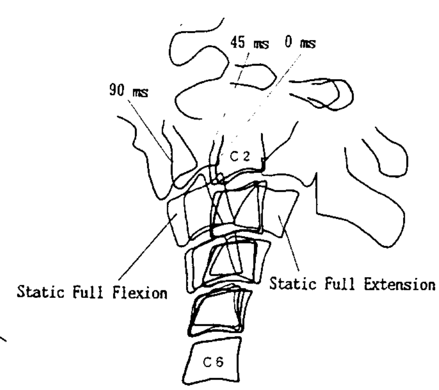

Figure 17. Superimposed Result of Cervical Motion in Frontal Impact(Run 23)

When the initial head position was rotated to the left or right, the excursion of the whole cervical spine was smaller than for the other head positions, because the intervertebral ligaments were pretensioned and less intervertebral movement was required to produce high resistive forces, thereby limiting the degree of relative motion between the vertebrae.

In frontal collisions, the head/neak motion exhibited a remarkable difference between the unbelted and lap-shoulder belted subjects. Restraint of the torso by the shoulder belt was equivalent to the thrusting of the torso by the seatback in a rear-end collision.

TEST RELATED CLINICAL FINDINGS

For 26 test subjects, 6 subjects (Runs 6,12,13, 15,19, and 24) reported mild discomfort after the test, but there were no objective changes observed in any medical tests. The majority of these symptoms were localized neck pain, beginning the morning after the test, and lasting 2 to 4 days. In all cases the discomfort resolved without treatment or therapy.

The test subject of Run 13 experienced muscle pain due to stretching of the sternocleidomastoid that resulted from rotation of the head. The test subject of Run 15 was conscious of mild discomfort of the trapezius due to overstrain of neck musculature, and the test subject of Run 19 experienced a slight ache in the lumbar region due to upward thrusting in the leaning-forward posture. However, for the other three subjects the cause of discomfort is unknown.

These discomfort symptoms probably result from micro-injuries of the musculature or soft tissues caused by the passive stretching in resisting inertial loads.

CONCLUSION

This was a limited study of the kinematic response and injury modes associated with head inertia loading of the neck. Because of the complex phenomena of head/neck motion, further research is needed before these kinematic responses can be generalized. However, the following conclusions can be made:

1. In rear-end collisions, with a simulated vehicle ΔV of less than 5 kph and a seatback equipped with a head restraint, the excursion of the cervical spine was never beyoned the normal range of motion.
2. In the leaning-forward or stooped-shoulder posture where the upper torso was initially away from the seatback surface, rear-end impact produced extension of the thoracic spine, resulting in upward axial acceleration of the cervical spine. This produced compression loading on the cervical spine, and it appeared that the neck length was shortened. At the same time, the cervical lordosis and the thoracic kyphosis were straightened, and cervical flexion occurred prior to extension.
3. In the upright and reclined postures with rear-end impacts, the torso was rapidly pushed by the seatback, and the chest and shoulders descended with rearward deflection of the seatback. The cervical spine was consequently not subjected to the upward acceleration and compression load that were present in the leaning-forward and stooped-shoulder postures.
4. In frontal collisions, the head/neak motion exhibited remarkable differences for the unbelted and lap-shoulder belted subjects. In the case with lap-shoulder belt, the subjects' jaw protruded forward as a result of the torso being restrained by the shoulder belt. In the unbelted case, the shape of the cervical spine remained essentially unchanged because there was no restraint of the torso.

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