INJURY BIOMECHANICS RESEARCH
Proceedings of the Twenty-fifth International Workshop

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Biomechanics of Human Cadaver Cervical Spine During Low Speed Rear Impacts

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ABSTRACT

It is hypothesized that a neck injury mechanism may exist during low speed rear-end impacts. Damage to the facet capsule and ligaments surrounding the cervical vertebrae can be a source of chronic neck pain and lead to long term degeneration of the cervical vertebrae. The purpose of this study is to measure the three-dimensional relative motions of each cervical vertebra and to obtain their kinematic responses and injury data. Eight tests using the Hybrid III dummy served as a baseline for current study. Four tests using two human cadaver specimens have been conducted. Testing apparatus consisted of a specially designed HYGE type mini-sled and a high-speed bi-planar x-ray system. The three-dimensional cervical vertebral motions during simulated rear-end automotive collisions were recorded and analyzed using x-ray images as well as planar photogrammetry. A nine-accelerometer mount on the head was used to obtain neck loads at the occipital condyle.

INTRODUCTION

Whiplash injury is defined as a non-contact acceleration-deceleration head-neck trauma. The cervical spine hyperextension would not occur with the introduction of head restraints. However, neck traumas have continued to occur with high incidence rates. Neck injuries in the automotive environment account for over 50 percent of all neck injuries. Most neck injuries occur in rear-end collisions (Ommaya et al., 1982). It has been suggested that the injury might occur before the hyperextension of the head. A few studies have been done with human volunteers (Ono et al. 1997, 1993; McConnell et al. 1995, 1993; Szabo et al. 1996, 1994; Geigel et al. 1994), but it is still not known what is the actual site of neck injury and the relation between injury and the head-neck motion in low speed rear impacts. The hypothesis of current research is that a major cause of neck injury and pain during low speed rear impacts is due to the sudden acceleration of the upper torso and stretch of facet capsule, and the injuries to these soft tissues can lead to long term pain and disabilities. The objective of this study is to quantify the motion of each vertebral body during rear impacts, from which ligament and soft tissue stretch and injury might be inferred.

MATERIALS AND METHODS

1. Dummy tests

Eight Hybrid III dummy experiments were conducted to establish a base reference for the head-neck kinematics in rear impacts. A specially designed and constructed HYGE type mini-sled was used to accelerate the subject. The sled system consists of a rigid seat and seatback without headrest. The seatback angle can be adjusted. The sled is propelled by a pneumatic piston and glides on a 20 foot long rail. A cable brake system, driven by a motor, can decelerate the sled at 0.3 g or more. The acceleration level of dummy tests ranged from 1.6 g to 14.3 g and the velocity ranges from 2.2 mph to 8.8 mph. To study the effects of ramping on the head-neck kinematics, two different seatback angles (0° and 20°) were used. The dummy was positioned in the rigid seat using a standard lap belt and a strap across the upper torso and seatback. Due to the lack of neck angle adjustment when using the lower neck load cell, the dummy's head and neck was reclined forward for the 0° seatback. The sled acceleration was measured with an uni-axial accelerometer. The dummy was instrumented with standard tri-axial head CG accelerometers, upper and lower neck load cells, and two accelerometers for the thorax accelerations in the longitudinal and vertical directions. A nine-accelerometer array (3-2-2-2) was attached to the head to determine the head CG linear and angular accelerations, the upper neck loads and the head rotations. On-board data acquisition system was used. Photographic targets were placed to the head, the neck, the shoulder and the seatback. The off-board lateral high-speed camera running at 200 fps or 300 fps recorded these targets.

The sled acceleration, the head CG accelerations, the thorax accelerations, and the upper and lower neck loads were processed and analyzed in accordance with SAE J211. Photo targets were digitized to obtain head rotation in the sagittal plane. The nine-accelerometer data were analyzed using the 3-2-2-2 method proposed by Padgaonkar et al. The upper neck loads and head extension-flexion angles from the nine-accelerometer unit were compared with the load measurements and the photogrammetry results.

Results

The initial peak values (before the maximum head extension) are summarized in Table 1. There were total of eight tests with four comparable groups of different seatback angle. The sled acceleration and velocity, the T1 and head CG accelerations, and the upper and lower neck loads are shown in Figure 1a and Figure 1b for the two different seatback angles.

The common responses of two different seatback angles are:

1. After the impact initiates, the thorax and head start to accelerate in the longitudinal and vertical directions about the same time.
2. The initial shear force in the lower neck is higher than in the upper neck.
3. Initial head flexion occurs before extension.

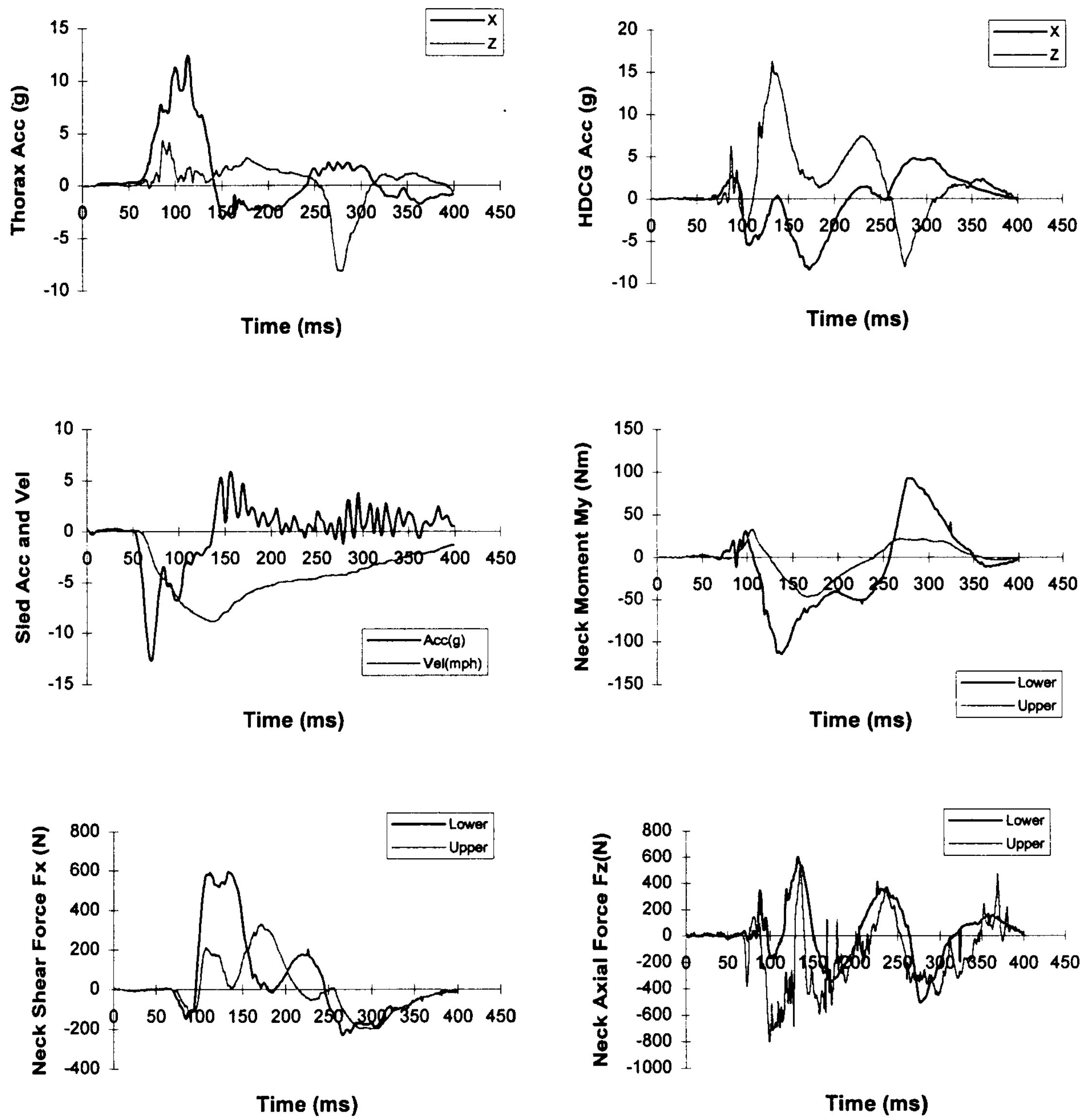

Figure 1a. Hybrid III dummy test data with 20^0 seatback angle
(D7, 12.7 g, 8.8 mph)

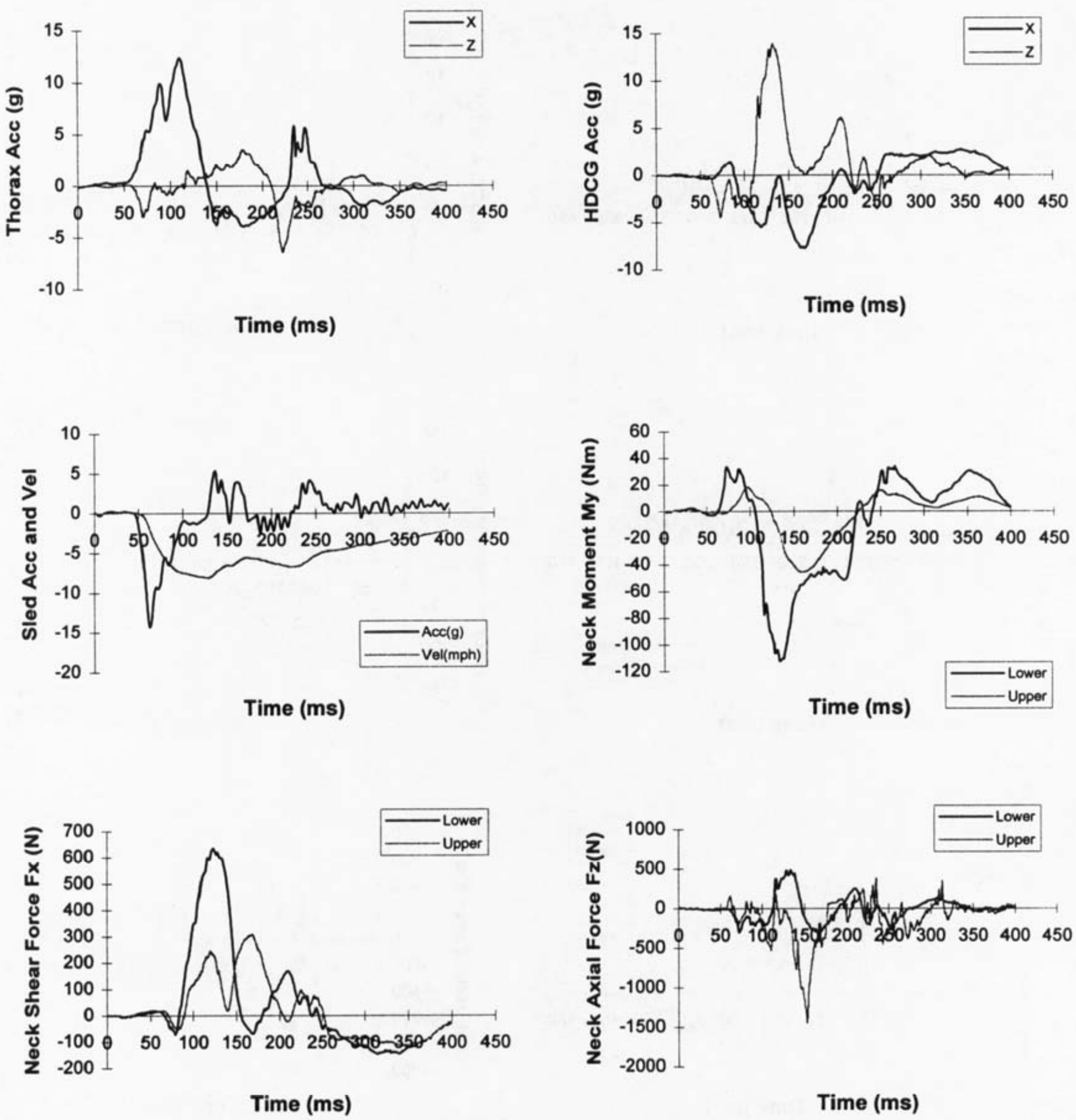

Figure 1b. Hybrid III dummy test data with 0^0 seatback angle
(D8, 14.3 g, 8.1 mph)

Table 1. Hyge Mini-Sled Rear Impacts with Hybrid III Dummy

			SB	Head			Thorax			Head
Run#	Sled Acc	Sled Vel	Angle	X Acc	Z Acc	Res Acc	X Acc	Z Acc	Res Acc	Extension
	g	mph	Degrees	g	g	g	g	g	g	Degrees
D1	-1.6	-2.2	20	-1.4	0.6	1.5	1.5	0.6	1.5	-11
D2	-2.6	-2.7	0	-2.6	0.8	2.7	1.8	-0.6	1.8	-26
D3	-3.9	-5.3	20	-2.9	2.4	3.6	3.9	1.3	4.1	-40
D4	-3.7	-4.9	0	-2.7	1.6	2.8	3.4	-0.9	3.4	-27
D5	-6.5	-6.6	20	-3.4	3.0	3.8	6.3	2.0	6.4	-38
D6	-8.4	-6.9	0	-3.4	7.5	8.0	6.6	-2.0	6.6	-71
D7	-12.7	-8.8	20	-5.6	16.3	16.3	12.4	4.4	12.5	-77
D8	-14.3	-8.1	0	-5.6	13.9	14.0	12.4	-3.0	12.4	-84

	Lower Neck					Upper Neck				
Run#	Fx	Fz (N)		My (Nm)		Fx	Fz (N)		My (Nm)	
	N	Compression	Tension	Flexion	Extension	N	Compression	Tension	Flexion	Extension
D1	78	-26	24	1	-16	55	N/A	N/A	2	-6
D2	171	-72	16	5	-29	107	-48	33	1	-12
D3	216	-90	99	13	-40	120	N/A	N/A	8	-18
D4	160	-105	17	21	-31	104	-64	17	8	-14
D5	298	-40	97	0	-41	137	N/A	N/A	3	-16
D6	382	-165	223	33	-78	146	-412	99	13	-33
D7	595	-179	602	30	-115	209	-679	392	32	-47
D8	636	-295	429	35	-113	240	-473	N/A	19	-46

The response differences between the two seatback angles are:
1. The thorax accelerates upward with 20° seatback and downward with 0° seatback angle.

2. Cadaver Tests

A high-speed bi-planar x-ray system is used to capture the instantaneous three-dimensional positions of seven cervical vertebrae (C1 to C7) and the first thoracic vertebra (T1). The x-ray unit is installed in the Motion Analysis Laboratory at Henry Ford Hospital's Bone and Joint Specialty Center. There are restrictions to the sled design such as limited space, limited viewing field of the x-ray system, and ease of transfer. A specially constructed HYGE type mini-sled with proper specifications to overcome those restrictions has been developed and fabricated. The sled can accelerate a cadaver specimen up to 15 g.

Two unembalmed female cadavers (Table 2) were tested. The specimens were x-rayed and physically examined prior to testing for any existing anatomic and pathologic abnormalities. Small lead balls were put to infraorbital notches and auditory meati to define the Frankfort plane. To obtain the kinematics of the cervical spine, 2 mm chrome steel balls were inserted into each vertebra (C1 to T1) in three locations: in the posterior spinous process, in the right or left transverse processes, and in the vertebral body at an anterior position. To minimize any surgical disruption to the neck structures, steinmann pins were used to find the cervical vertebrae locations, then 2 mm holes were drilled on the bone, and the steel balls were inserted into the holes percutaneously via a tube and a probe. X-rays were used to guide the placement. Figure 2 shows one x-ray taken during the marker insertion procedure. CT scan of the neck is used to determine the exact locations of the vertebral metal balls and to reconstruct the three-dimensional geometry of the cervical spine. A slice of CT scan with one marker in the posterior spinous process and one marker in the vertebral body is shown in Figure 3.

Table 2. Cadaver Specimen

CAD #	Gender	Age	Weight (kg)	Height (cm)
558	Female	81	41	24
582	Female	50	73	25

The high-speed bi-planar x-ray is a continuous, nongated system. The unit has two sets of x-ray heads and intensifiers mounted to a dual overlapping gantry fixture. The two pairs are 60° apart in the horizontal plane. The x-ray vision range is about 190 mm in the longitudinal direction and 140 mm in the vertical direction. Three-dimensional motions of the cervical spine were quantified from the instantaneous positions of the chrome balls. The critical event in the neck occurs within 200 ms from the onset acceleration. X-ray images of vertebral motion were acquired at 250 frames per second.

Four tests using two specimens have been conducted using 20° and 0° seatback angles. The subjects were positioned in the rigid seat using a standard lap belt and a strap across the upper thorax and seatback. The head was held approximate vertical to obtain the neutral position of the cervical spine.

Figure 2. X-ray of Steinmann Pin Locations during Marker Insertion

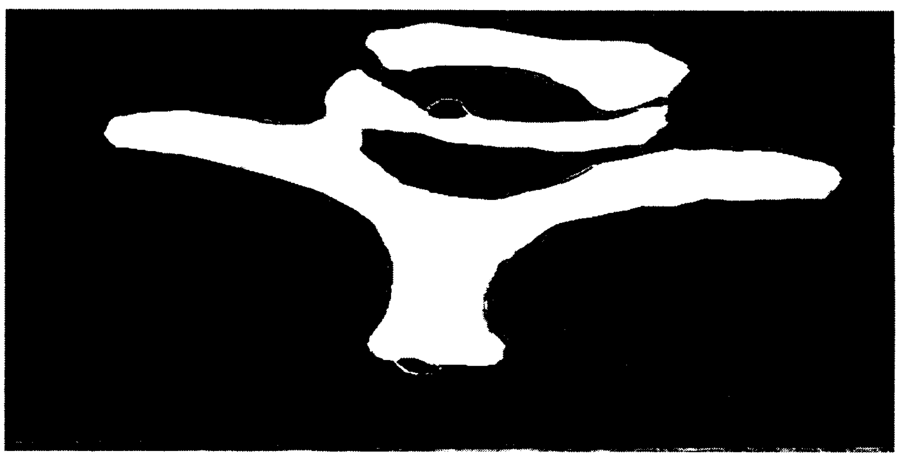

Figure 3. CT Scan of Cervical Vertebral Body

The nine-accelerometer module was used for the head accelerations as well as calculating the loads on the neck at the occipital condyle. The 3-2-2-2 array was screwed to the top of the skull. A redundant angular velocity sensor (ARS-01) was attached to the 3-2-2-2 array about the lateral axis. A triaxial accelerometer unit was mounted to the T1 vertebral body. The sled acceleration was recorded in the +x direction. A test setup is shown in Figure 4.

Lateral planar x-rays of the head and neck were used to measure the relative locations of the nine-accelerometer mount origin to the head center of gravity and to the occipital condyles. This data was used to obtain the head linear and angular accelerations at the center of gravity of the head and the neck loads acting at the occipital condyles.
Photo targets were placed to the head, T1 and seatback. A floor mounted high-speed camera running at 200 frames per second recorded the head-neck motion in the sagittal plane. The films were digitized to obtain the head and T1 rotations.

Figure 4. Cadaver Test Setup

The sled acceleration and T1 accelerations were processed according to SAE J211. The nine-accelerometer data were analyzed using the 3-2-2-2 method. The calculated head angular velocities about the lateral axis were compared with the angular sensor measurements and the head rotations in the sagittal plane were compared with the film analysis results. The shear force, axial forces and bending moments at the occipital condyle were calculated.

A custom program from the Motion Analysis Laboratory at Henry Ford Hospital was used to retrieve the landmarks from the x-ray images of the cervical vertebral markers. A Motion Analysis System was used to track the marker three-dimensional positions. The tracking accuracy is 0.2 mm. The landmarks from x-ray images were correlated to the CT scan coordinates to find the marker locations in the cervical spine.

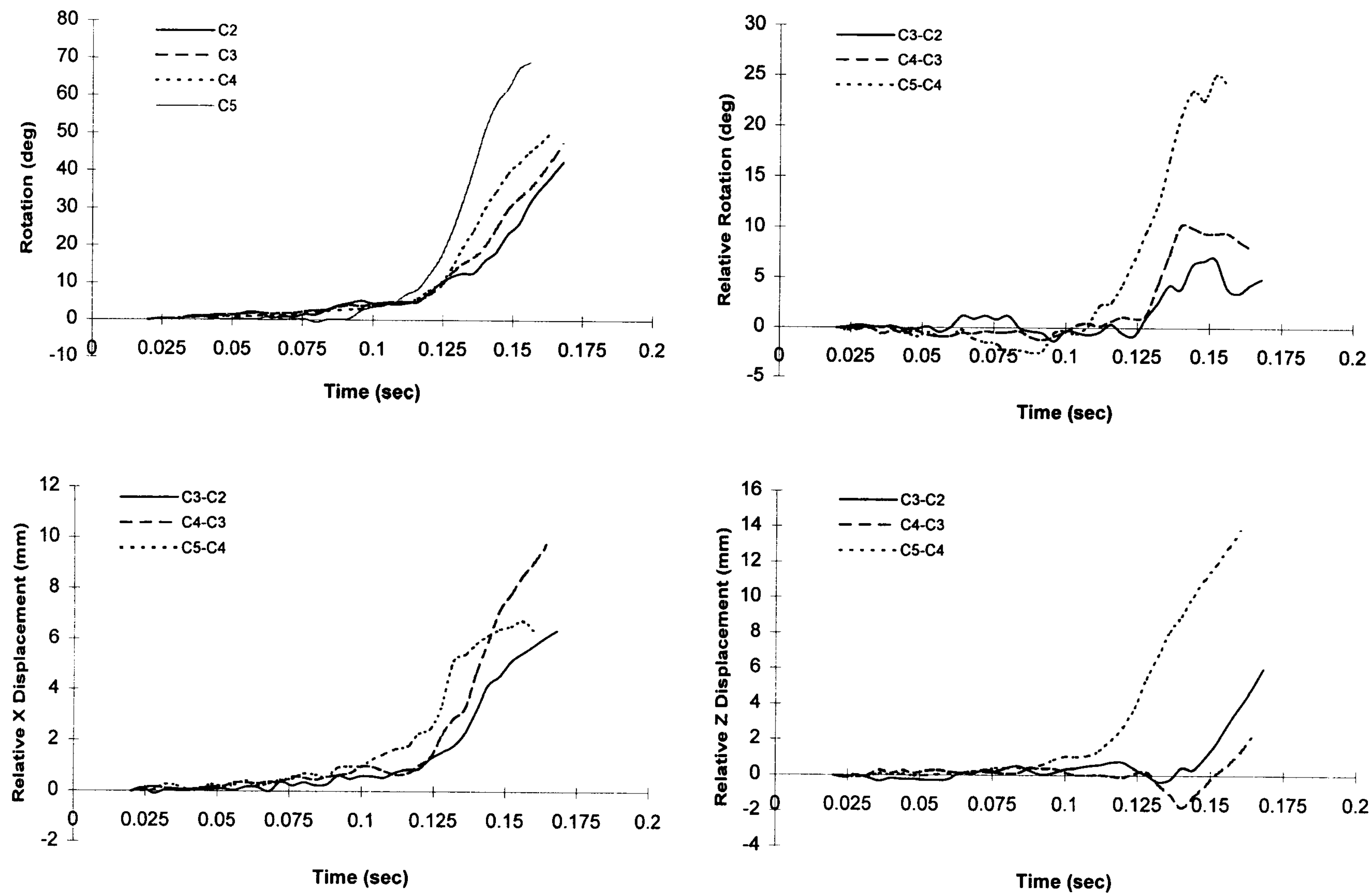

Figure 5a. CAD 582 cervical vertebral body (C2 to C5) rotations and displacements (20^0 seatback angle)

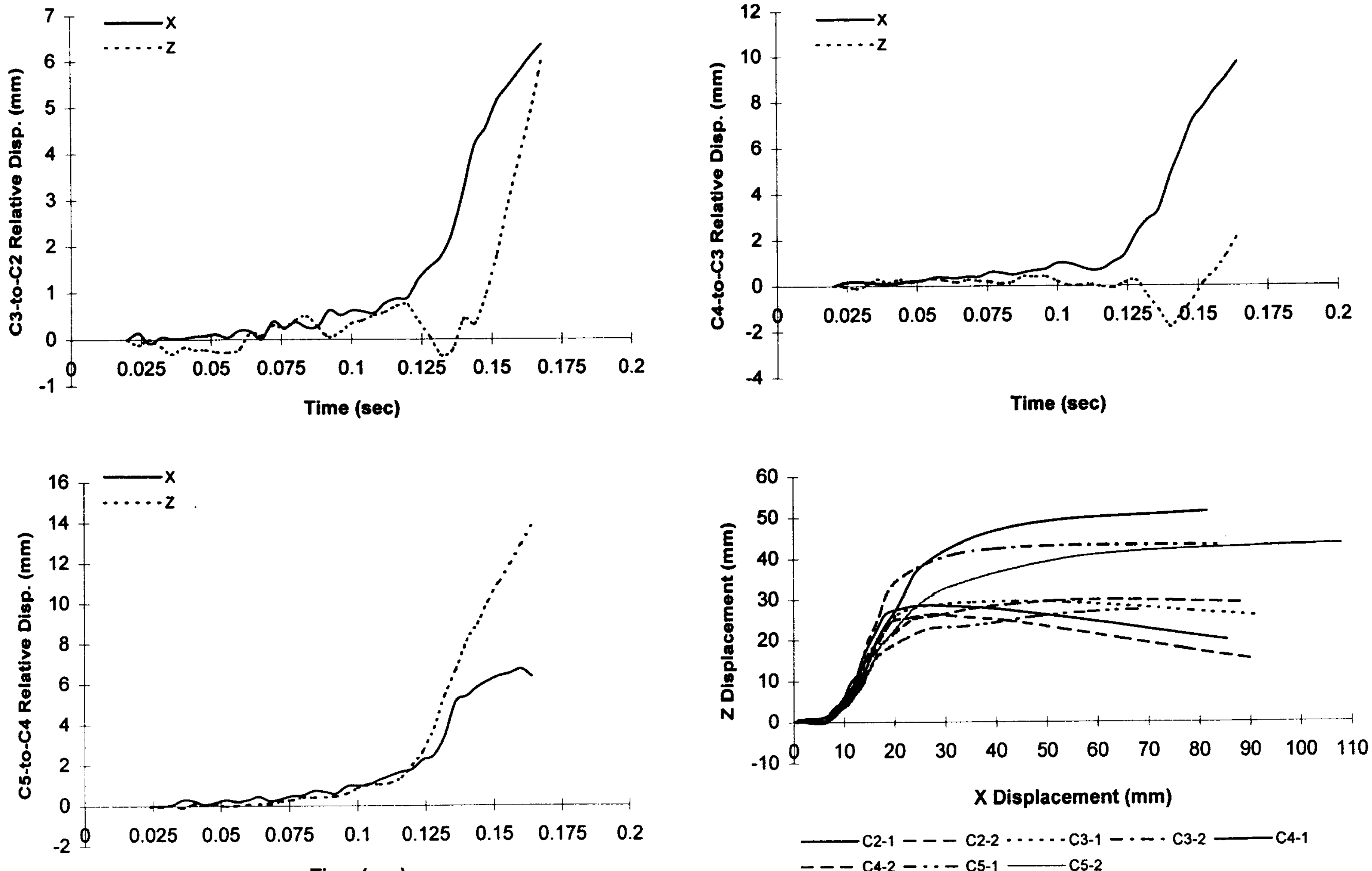

Figure 5b. CAD 582 adjacent cervical vertebrae relative displacements and marker trajectory(20^0 seatback angle)

RESULTS

Cervical marker tracking results from cadaver #582 is shown in Figure 5a and Figure 5b. The test acceleration is 6.40 g and the sled velocity is 6.83 mph. The rotations of C2 through C5 were obtained in the sagittal plane. The relative rotations and displacements were calculated. It shows that significant rotations happened in the lower cervical spine. The lower vertebral body rotated more than the adjacent higher ones. The displacements were expressed in the laboratory coordinate system. The lower vertebra moves upward relative to the upper one in this system. Autopsy on this specimen found no neck injury. To better understand the relative motions between each cervical vertebra, the displacements need to be transferred to a coordinate, which is fixed to the vertebral body.

CONCLUSION

This ongoing study provides a method, which can measure the cervical spine kinematics directly. Although preliminary, the results from four impacts suggest relative displacements and rotation between the adjacent cervical vertebral bodies. More work needs to be done to better quantity each cervical vertebra kinematics and to obtain soft tissue injury in the future.

ACKNOWLEDGMENT

This study is financed by GM pursuant to an agreement between GM and the U.S. Department of Transportation. The effort of Dr. Ruhan Iskendar of Wayne State University Bioengineering Center is deeply appreciated.

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DISCUSSION

PAPER: **Biomechanics of the Human Cadaver Cervical Spine During Low Speed Rear Impacts**

PRESENTER: Bing Deng, Wayne State University, Detroit, Michigan

QUESTION: Frank Pintar, Medical College of Wisconsin

I think that you may be getting some artificial compression in the neck because of the rigid seatback. Ono's work seems to indicate that there is more X translation with a softer seatback. Do you have a comment?

ANSWER: The reason we chose a rigid seat is that we didn't want to study any parameters for seat stiffness or configuration.

Q: But if your seatback is causing an artificial phenomenon in your neck, it is not correlating to the real world injuries.

Q: Koshiro Ono, Japan Automobile Research Institute

Yesterday, I showed results for the soft seatback. More important things to compare to the motion of T1 are the straightening and horizontal motion. The rotation or backward motion of the upper torso comes from the rotations. This rotation will be associated with some upward motions. This is probably the same thing for the volunteers.

A: Are you saying your neck motion looks like that, because I thought yours translates a little bit more than theirs from what I've seen from your data?

Q: The upper torsos rotate also.

A: You have more shoulder rise. I didn't see that in her simulations.

Q: We can discuss this in more detail later.

Q: Guy Nusholtz, Chrysler Corporation

A question on a different subject. How much resolution do you get from frame to frame with regard to the targets you're pulling off of the x-rays.

A: I can't remember the exact figure.

Q: Another question which maybe can partially answer that. Is there enough resolution from frame to frame to be able to differentiate it or do you have too much noise?

A: No. The x-ray images are very clear.

Q: Yes, but the error from frame to frame when you pull the digital information off is going to have some inherent error either because of the x-ray intensity or changes in the shadow graph. You'll have some error and when you try to differentiate it, you may or may not be able to get good velocities. So, have you attempted to differentiate the data?

A: We are focusing on the initial event, which is like 45 frames from the beginning. That is what I show in the video.

Q: Koshiro Ono, JARI

I would like to confirm the limitation which you mention in your presentation. That is, the different motions of the upper cervical vertebrae, like C1, C2, or C3. Did you show that after the impact, the upper cervical bodies would be moved rather than the lower bodies?

A: It is moved upward compared to the lower part. We saw significant motion in the lower part, not for the upper part. The upper part was first moved upward.

Q: It is just the upper part of the body as we rotate at first. You showed the slide.

A: I don't think it is rotated first. The rotation may be due to the curvature of the neck but it is moved upward first, and the rotation occurs first for the lower part.

Q: OK. Thank you.