SAE TECHNICAL PAPER SERIES

930094

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Reprinted from: Human Surrogates: Design, Development and Side Impact Protection (SP-945)

The Engineering Society For Advancing Mobility Land Sea Air and Space®
INTERNATIONAL

International Congress and Exposition
Detroit, Michigan
March 1-5, 1993

400 Commonwealth Drive, Warrendale, PA 15096-0001 U.S.A. Tel: (412)776-4841 Fax:(412)776-5760

ISSN 0148-7191

Printed in USA

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ABSTRACT

The head motions of a human driver and a Hybrid III Anthropometric Test Device (ATD) right front passenger were measured in low-speed rearend impacts (velocity change (ΔV) $\leq$ 8 kph) with high speed film and accelerometers. Data were analyzed from three crashes with the same human driver (weight similar to ATD) at ΔV's of 3.9, 6.6 and 7.8 kph. The results indicate that the human's and ATD's head have roughly similar basic patterns of motion: a post-impact period where the head is stationary with respect to the earth (Phase I), a period where the head rotates rearward with respect to the vehicle (Phase II), a subsequent period where the head rotates forward with respect to the vehicle (Phase III) and a final period where the head settles into a post-impact rest position (Phase IV). The human's head motion tended to be more complex than the ATD's head motion during Phases II and III. These results suggest that the Hybrid III head kinematics are different from human head kinematics in the same low-speed rearend collisions and care must be used in predicting human head motion and whiplash injury potential from Hybrid III measurements in low-speed rearend impacts.

INTRODUCTION

Reducing the overall number and the severity of whiplash injuries in rearend impacts has proven to be a difficult task for the automotive safety community. Neck extension beyond physiological limits was thought to be the cause of the whiplash injury[1] and with the issue of FMVSS 202 in 1969 head restraints were placed in all passenger vehicles. Unfortunately, it soon became clear that head restraints were not an absolute cure for whiplash injuries in low-speed rearend collisions. According to one study, integral restraints reduced whiplash injury risk by 28 percent and adjustable head restraints reduced whiplash injury risk by 17 percent[2]. The question that still needs to be answered is the identification of the injury mechanism or mechanisms that cause the whiplash injury. Until this question is answered, future progress in the reduction of whiplash injuries will be limited.

Biodynamic Research Corporation has undertaken further study of vehicle behavior and occupant kinematics in low-speed rearend impacts. The initial phase of the study began in February of 1991 with a series of low-speed vehicle crash tests performed in San Antonio, Texas. Changes in velocity (ΔV) of the vehicles struck in the rear ranged from 4.0 kph to 8.0 kph. All of the struck vehicles contained an instrumented human driver and some contained a 50% male Hybrid III Anthropometric Test Device (ATD) as the right front passenger. Two of the main objectives of this series of crash tests were to obtain preliminary information on the kinematics of the human head and neck in low-speed rearend impacts, and to compare the Hybrid III's head and neck motion with the human's motion. This paper presents the comparison of the human's and Hybrid III's head and neck motions. A more detailed presentation of the human's kinematics is presented elsewhere.[3]

Two recent studies have looked at the performance of human surrogates in low-speed rearend impacts, although neither used a Hybrid III ATD. Romilly, et. al[4] used a pendulum to represent the bullet vehicle. The focus of this study was to determine the effect of rear bumper stiffness on occupant protection in rearend impacts. A restrained Hybrid II ATD was used as the human surrogate. These authors observed that when the occupant rebounded forward, the Hybrid II's shoulders led the head. They concluded that the difference in the relative head and shoulder motions may be a cause of the whiplash injury.

Emori, et. al[5] simulated rearend impacts with vehicle-to-vehicle crashes. Their ATD was a 30 GM-JM50-67 (Ito Seiki) with a neck modified to fit a measured occipital condyle moment versus neck extension angle curve[6]. The amount of neck extension was used as an indicator of the severity of the whiplash injury. These authors concluded that a headrest is effective in reducing the amount of extension and recommend deformable bumpers to reduce the peak accelerations experienced by the struck vehicle and its occupants.

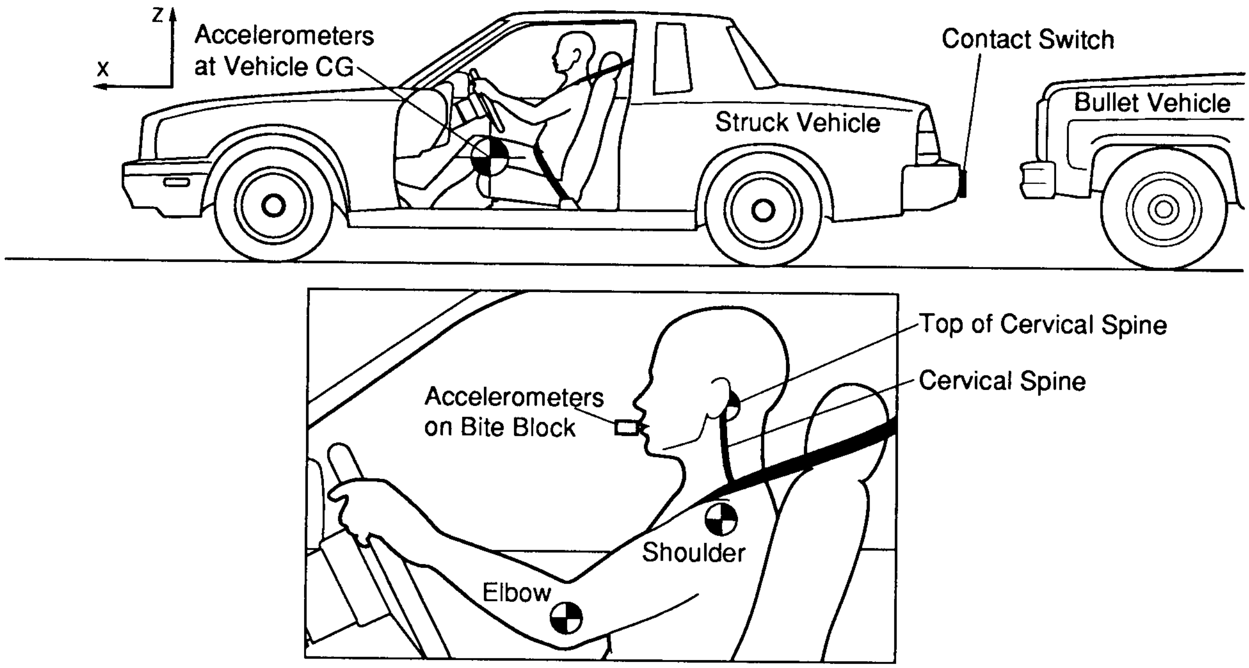

Figure 1. Schematic of the test setup showing the vehicle orientations, accelerometer positions, targets on the driver and the earth-fixed coordinate system.

METHODS

OVERVIEW — A series of ten low-speed front end (bullet vehicle) into rearend (struck vehicle) crash tests were performed under controlled conditions. Figure 1 provides an overview of the test setup and the instrumentation. In the three tests reported in this paper, a male test subject was the restrained driver and a 50% Hybrid III ATD was the restrained right front passenger of the struck vehicle. The same male test subject and Hybrid III ATD were used in all three tests.

VEHICLES — There were four vehicles used in the tests; a 1986 Dodge 600 convertible, a 1984 Buick Regal Limited coupe, a 1984 Ford Club Wagon van and a 1984 GMC 1500 pickup truck. There was no evidence of structural damage on the vehicles and each was in roadworthy condition with standard equipment. The convertible and coupe had energy absorber bumper systems, and the truck and van had bumper systems that were rigidly attached to the frame. Although each vehicle remained in stock condition, the testing protocol required a number of modifications. The vehicle occupants had to be visually accessible for the cameras, so the upper portion of the Ford van's left B-pillar and the front doors of each vehicle were removed. The head restraints in the convertible and the coupe were kept in the raised position. The van and pickup did not have head restraints. Each vehicle's original equipment 3-point restraint system was used throughout the tests. Vehicles were checked prior to each test and if any bumper assembly damage was discovered, it was repaired with new parts.

TEST SITE — The test site was established on a level section of paved roadway. The bullet vehicle was accelerated to the impact speed by allowing it to roll down a ramp. The bullet vehicle's starting position on the ramp was calibrated before each test run to ensure that the collision velocity was in the desired range. The actual closure speeds and the changes in velocity of both vehicles were determined by high speed film, high speed video and an electronic speed trap.

INSTRUMENTATION — Each vehicle had three orthogonal accelerometers (Endevco #7920-10 and #7920-30) mounted on the frame at the vehicle's center of gravity (CG) to measure vehicle accelerations. Three linear orthogonal accelerometers (Endevco #7920-10 and #7920-30) were also mounted on bite blocks of the human and the ATD to measure head accelerations. The human's bite block consisted of an aluminum strip with a mouth piece on one end the accelerometers mounted on the end that protruded from the mouth. With the jaw normally closed, this configuration firmly fixed the accelerometer assembly to the human's head. The ATD's mouthpiece had a configuration similar to the external section of the human's and this section was bolted to the dummy's mouth. Data was collected on a PAC-5800 data acquisition system (DAS) at a sampling rate of 8000 samples/sec.

High speed cameras (Redlake LoCam, Model #51) were placed on tripods mounted on the ground, one facing the driver and another facing the right front passenger door opening. The film speed was a nominal 500 frames/sec and the film had a timing mark that operated at 100 Hertz. Several tripod mounted VHS videos also recorded the tests. A contact switch placed on the rear bumper of the struck vehicle set off a flash and generated an electronic signal that was sent to the DAS. The electronic signal and flash were used to coordinate the transducer data with the photogrammetric data.

TEST SUBJECT PREPARATIONS — The proposed test protocol was evaluated by the University of Texas Health

Science Center Institutional Review Board (IRB) and IRB Protocol #9010099006 of the University of Texas Health Science Center (under DHHS Regulation 46.110(3)) approved the use of human test subjects from the staff of Biodynamic Research Corporation. The healthy male test subject used in the three tests described in this report was 50 years of age, weighed 78 kg, and had a height of 180 cm. The test subject had passed a pre-test physical that included radiographic imaging studies of the cervical, thoracic and lumbar regions of his spine. This subject participated in other low-speed crash tests (seven total) and did develop temporary symptoms of mild cervical strain that were resolved within 24 hours of the tests.

Several visual targets were placed on the left side of the human driver (see Figure 1). One target was placed below and slightly behind the left external auditory canal over the mastoid prominence as an approximation of the lateral projection of the upper end of the cervical spine. Targets were applied to the skin over the subject's left neck, simulating the lateral projection of the cervical spine. The subject wore a tight garment and targets were placed approximately over the left gleno-humeral joint (shoulder) and lateral left elbow. The Hybrid III ATD wore a similar garment and had similar right side anatomical reference point markings applied, with the exception of the neck which was not marked since the ATD's neck is exposed. A stiff yellow u-shaped rod was placed on the end of the accelerometer mount to facilitate tracking the driver's and ATD's bite block.

DATA REDUCTION — The position of the targets on the human driver and the ATD was digitized on the 16mm film at 10ms intervals. These positional data were then splined (cubic spline) and filtered (alpha trimmed mean filter). The rotational displacement and rotational acceleration of the head were obtained from these data.

All accelerometer data were filtered to eliminate short term transients. Because of the head's curvilinear path, the bite block accelerometers measured accelerations that are composed of translational and rotational accelerations. The rotational accelerations determined from the high speed film analysis were mathematically removed from the transducer acceleration data to provide the translational accelerations of the head in an earth-fixed inertial reference frame. In this inertial reference frame, the x-axis points forward, the z-axis points up and the y-axis points to the left (See Figure 1). Lateral motions in these tests were negligible and information on occupant motion in the y-axis is not presented.

RESULTS

CHANGES IN VELOCITY - Table I lists the vehicles involved in each of the three crashes and the ΔV of the struck vehicle. The test weight of each vehicle is given in parenthesis.

The velocity versus time curve for the struck vehicle in each of the three impacts is shown in Figure 2. In this graph and all of the following graphs time zero is the time that the vehicles make first contact. In each test, the struck vehicle had achieved its final post-impact velocity approximately 120ms after impact.

Test	Struck Vehicle	Bullet Vehicle	ΔV of Struck Vehicle
1	Coupe (1492 kg)	Pickup (1777kg)	3.9 kph (2.4 mph)
2	Van (1937kg)	Pickup (1777kg)	6.6 kph (4.1 mph)
3	Coupe (1492kg)	Convertible (1252kg)	7.8 kph (4.9 mph)

Table I. Vehicle Configuration and ΔV of Struck Vehicle in Each Test

GENERAL KINEMATICS OF THE HUMAN'S AND ATD'S HEAD — The general kinematics of the head of the human and the ATD were roughly similar as both exhibited the same four distinct phases of post-impact motion. These four phases of motion are based on the rotational motion of the head in the sagittal plane and are shown schematically in Figure 3. The arrows indicate head motion as seen from the vehicle reference frame, i.e. as seen by a viewer who is rigidly attached to the vehicle. Phase I is the period of time

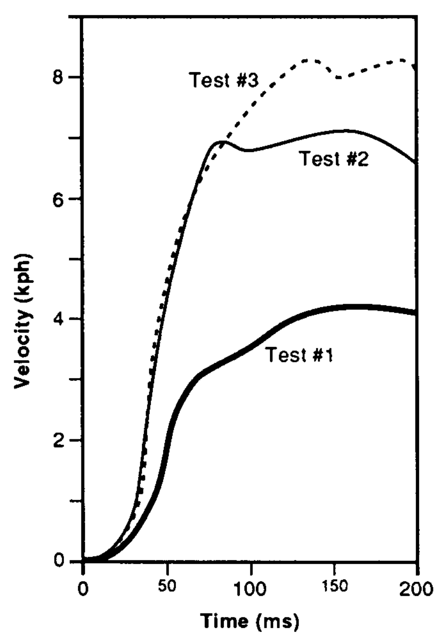

Figure 2. Velocity of the struck vehicles during the first 200ms after impact.

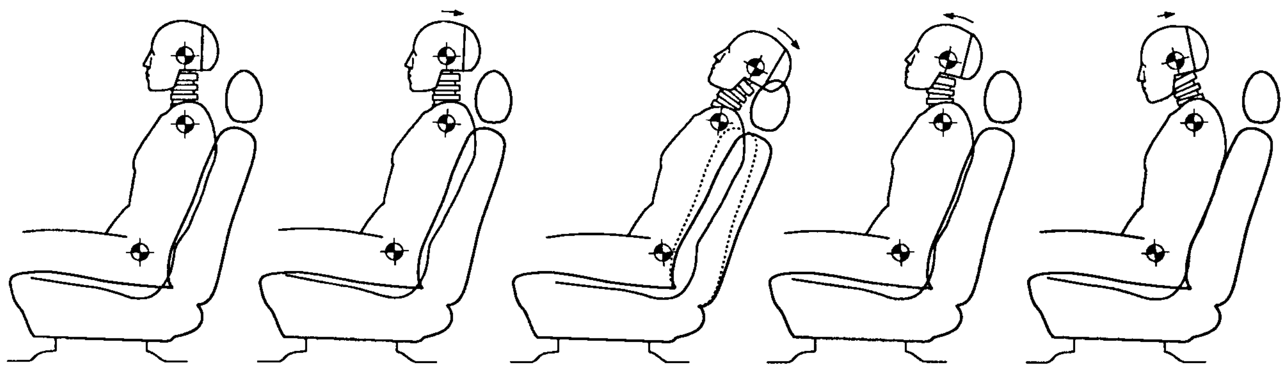

Figure 3. The Pre-impact Position and the Four Phases of Head Motion as seen from the Vehicle Reference Frame. The dashed line in the Phase II scene represents the undeformed position of the seatback.

after impact in which the head appears to translate rearward as the torso sinks into the forward moving seatback. As viewed from the earth-fixed inertial reference frame the head appears to be stationary. During Phase II, the head does an extension rotation and moves towards the rear of the vehicle. Phase III is the period of time in which the head rebounds forward; it reverses rotation and moves towards the front of the vehicle. Once the head's forward motion has stopped, the head motion enters a restitution period, called Phase IV, in which the head settles into its post-impact rest position.

Table II gives the post-impact time that each phase began for the human's and the ATD's head. Phase I always starts at the time of initial contact, time zero. The similarity in times indicates that the timing of the human's and the ATD's fore-aft head movements are similar, although the ATD's head appears to respond somewhat quicker. The duration of Phase II in Test #3 is shorter than the Phase II in the less severe crashes because the human's and the ATD's head made contact with the head restraint, which limited the rearward excursion and shortened Phase II. There were no head contacts with the head restraint in Tests #1 and #2 (the van in Test #2 did not have head restraints).

The actual duration of each phase was determined from the rotational motion of the head. Theta (Θ) represents the angle between a line that runs between the end of the bite block and the craniocvervical junction of the occupant and the horizontal plane. Figure 4 shows Θ for the ATD's head during the post-impact period in Test #2 that includes Phases I, II, and III. A schematic describing Θ is shown in the insert in Figure 4. The initial angular position at time zero is the pre-impact orientation of the head. An increase in Θ indicates that the head is rotating rearward or farther into extension; a decreasing Θ indicates that the head is rotating forward.

Phase I in Test #2 starts with the ATD's head in a pre-impact position of 9° and the period of no rotation lasts for about 50ms. During Phase I, the vehicle accelerates and causes the front seats to move forward approximately 2.5cm (1.0 in.) in Test #2. The occupants' bodies remain essentially

TEST #	ΔV (kph)	OCCUPANT	II	III	IV
1	3.9 (2.4 mph)	Human ATD	65ms 50ms	235ms 200ms	425ms 375ms
2	6.6 (4.1 mph)	Human ATD	50ms 50ms	230ms 225ms	435ms 380ms
3	7.8 (4.9 mph)	Human ATD	55ms 45ms	180ms 170ms	335ms 350ms

Table II. Post-Impact Time in Millisecond (ms) that Each Phase Begins

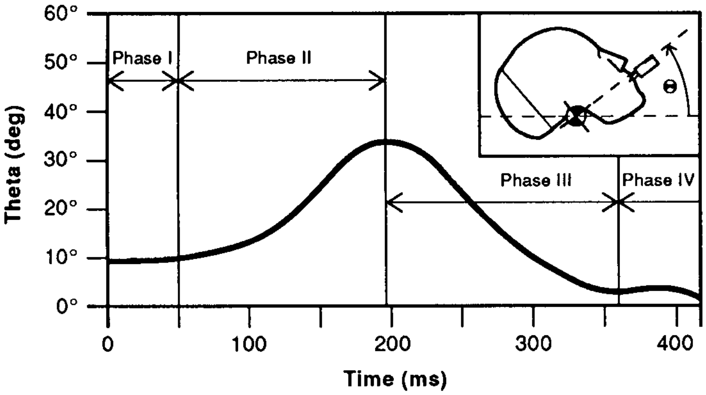

Figure 4. Angular position (Θ) of ATD's head in Test #2 with Phases I, II and III indicated. The insert describes Theta.

motionless in inertial space and the occupants appear to sink into the seatbacks. Although the seatback is being compressed by the occupant, it does not exert enough force during Phase I to noticeably move the occupant's torso forward. In these tests, Phase I lasted for approximately 45 to 65ms.

Phase II, the period in which the head moves rearward relative to the vehicle, lasts for 125ms to 175ms in these tests. Early in Phase II, the hips and back begin to move forward in inertial space as the deformed seatback generates enough force to accelerate the torso forward. The inertia of the head causes the head's forward motion to lag behind the torso's forward motion. To an observer in the vehicle, this appears as a rearward motion of the head. At approximately 100ms, the seatback reaches its maximum rearward rotation of about 10°. At the end of Phase II, the head is at its maximum rearward position relative to the vehicle and its maximum extension angle, 33° in Test #2. This places the ATD's neck in tension and this tensile force accelerates the head forward. The peak forward acceleration of the ATD's head occurs at the end of Phase II and the beginning of Phase III.

Phase III is the period in which the head moves forward in the vehicle and it lasts for approximately 175ms. Near the midpoint of Phase III, the rebounding torso is being retarded by a tightened restraint system. The impact had a pre-tensioning effect on the restraint system. As the vehicle moved forward, the occupant's torso (both human and ATD) sank into the seatback and the normal tension on the webbing was relieved. This allowed approximately 5.0 to 7.5 cm of webbing to be taken up by the retractor, which pre-tensioned the restraint system. As the torso's rebound was stopped, the head continued to move forward relative to the vehicle. At the end of Phase III, the head reached its most forward position relative to the vehicle. In Test #2 the ATD's head had rotated about 7° past its pre-impact angular position at the end of Phase III.

The restitution period, Phase IV, lasts for approximately 200ms. The head and torso are travelling at approximately the speed of the vehicle by 450ms and all of the impact related movements are damped out as the occupants settle into their post-impact final positions.

ROTATIONAL MOTION OF THE HEAD — Figure 5 shows Θ for the human driver and the ATD in all three crashes. The similar phasing of the rotational motion of the human's and ATD's head is apparent in the graphs. The human's head was rotated further forward prior to impact in all of the tests as indicated by the smaller pre-impact angle. This was due to a conscious effort by the human driver to maintain normal forward vision through the windshield. The human's head returned to an angle of approximately 5° by the end of Phase III which was similar to its pre-impact angle in all tests except Test #1. This is in contrast to the ATD's head,

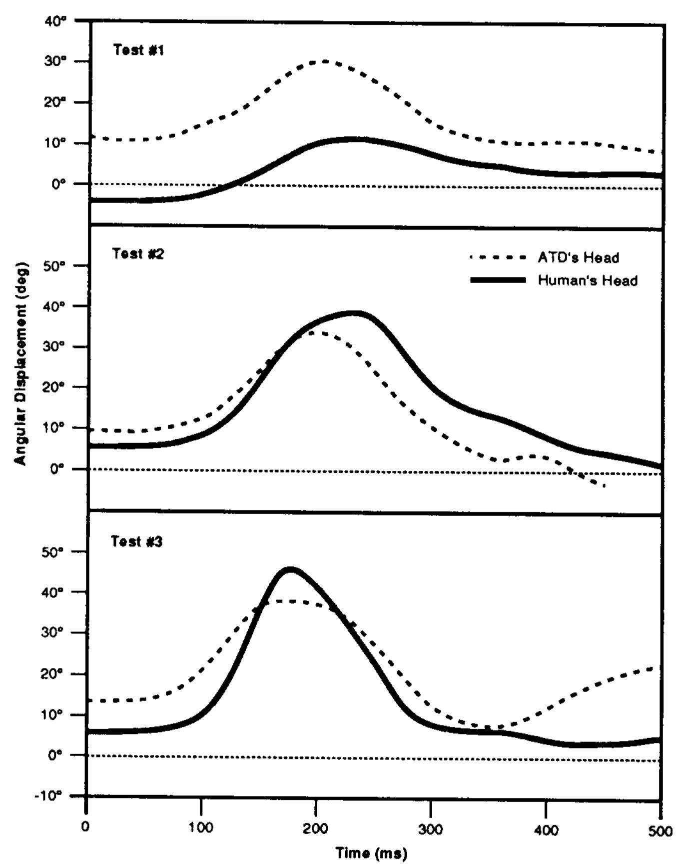

Figure 5. Theta for the ATD's and the human's head in Tests #1, #2 and #3.

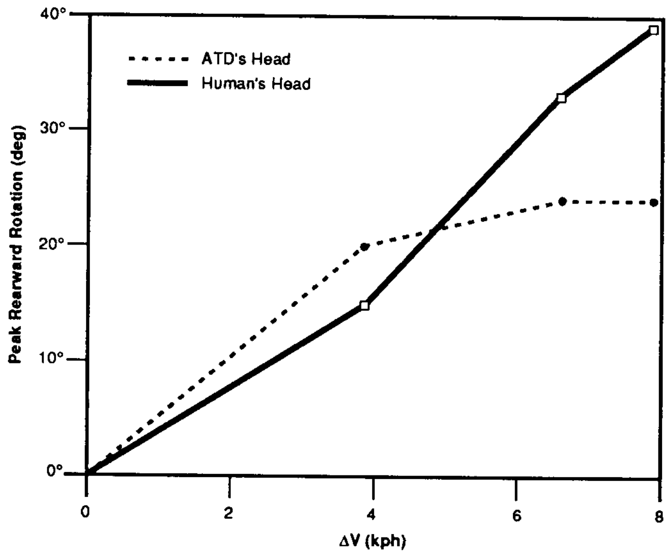

Figure 6. Peak rearward rotation vs. ΔV for the human's and ATD's head.

which rotated approximately 7° past the pre-impact angle by at the end of Phase III in the more severe impacts in Test #2 and #3.

While the overall rotational motion pictured in Figure 5 indicates the timing of rotation is similar for the human's and ATD's head, there were distinct differences in the center of rotations of the head motions and the amount of rotation. The centers of rotation were approximated using the photogrammetric data. The ATD's head and neck acted like a pendulum, a mass (head) on the end of a flexible arm (neck). Since the craniocervical junction of the Hybrid III is not very flexible in the sagittal plane, most of the head rotation is due to neck bending and the center of rotation is in the neck. The center of rotation for much of the motion of the human's head was in the head and appeared to be at a location between the CG of the head and the occipital condyles.

The maximum extension rotation is the change in Θ between the pre-impact angular position and the angular position that occurs at the end of Phase II. The maximum rearward rotation of the head is shown in Figure 6 for the three impact tests as a function of the ΔV. In the more severe impacts, the human's head experienced a greater amount of rotation than did the ATD's head. The excursion of the ATD's head appears to be relatively insensitive to ΔV, while the test subject's head exhibits an almost linear relationship between ΔV and the amount of rearward rotation over the range of ΔVs in these test impacts.

The peak rotational accelerations for the ATD's head also appear to be relatively insensitive to ΔV. Figure 7 shows the peak rotational accelerations during the rearward and forward rotations as a function of ΔV. The peak rotational accelerations of the human head increased as the severity of the crash increased while the peak rotational accelerations for the ATD's head remained fairly constant within the crash severity range investigated. The peak forward rotational accelerations were higher than the peak rearward rotational accelerations for both the human's and the ATD's head.

TRANSLATIONAL MOTION OF THE HEAD/NECK — The translational motions are defined in the earth-fixed reference frame shown in Figure 1. There were distinct differences between the movement of the top of the human's and ATD's cervical spine. The change in the vertical position

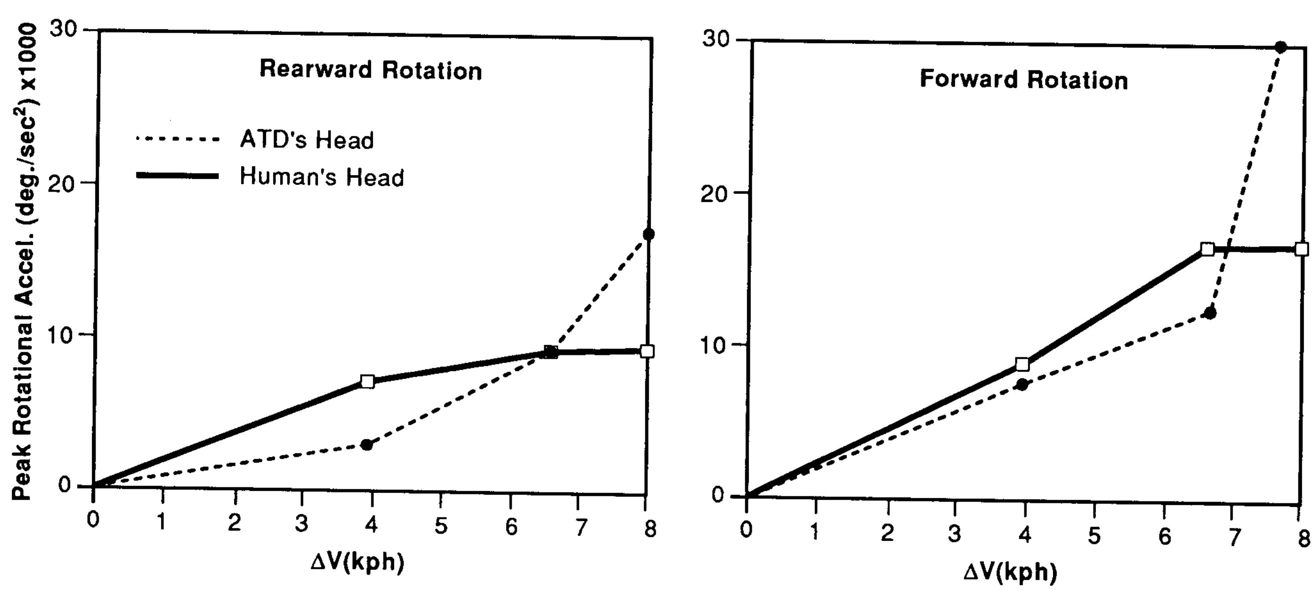

Figure 7. Peak rotational accelerations vs. ΔV. Left: During the rearward rotation. Right: During the forward rotation.

	Test #1	Test #2	Test #3
Human	- 0.0 cm (0.0 in)	+ 1.0 cm (+ .4 in)	+ 1.5 cm (+ .6 in)
ATD	- 2.0 cm (- .8 in)	- 1.5 cm (- .6 in)	- 4.3 cm (- 1.7 in)

Table III. Change in Vertical Position of the Head

of the top of the neck from the beginning of Phase II to approximately the middle of Phase II is given in Table III for the human's and the ATD's head. The top of the human's cervical spine tended to rise during the first half of Phase II while the ATD's always dropped. The human's hips also tended to rise more than the ATD's hips.

The x-axis accelerations for the CG of the human's and the ATD's head are shown in Figure 8 for all three tests. A positive acceleration represents an acceleration towards the front of the car. The main forward acceleration (positive g's) of the ATD's head occurred when the ATD's head was near its maximum rearward rotation, the end of Phase II, and was due to tensile forces in the neck pulling the head forward. This acceleration pulse was characterized by a single peak. The acceleration pulse for the human's CG was composed of two distinct peaks, one that occurred at the middle of Phase II and another that occurred at the end of Phase II or early in Phase III. The height of the double peaks for the human's head are lower than the height of the single peak in the acceleration trace for the ATD's head. The relative height of the two peaks in the human trace changed as crash energy increased. The first peak was the highest in Test #1 (3.9 kph ΔV), the two peaks were about equal in Test #2 (6.6 kph ΔV), and the second peak was the highest in Test #3 (7.8 kph ΔV).

DISCUSSION

The aim of this study was to compare the Hybrid III's head and neck kinematics with a human test subject's head and neck kinematics in the same low-speed rearend impacts. While whiplash injuries involve the neck, our results have focused on head motions for two reasons. First, potentially injurious neck forces can be inferred from rapid or unphysiological head motions. Second, head motions are easily measured on human subjects while neck forces are not. This report is based on only three tests using the same human subject, therefore it should be viewed as a preliminary study that does not address possible human-to-human differences and ΔVs greater than 8.0 kph. Only two vehicles were used as struck vehicles in these tests, thus vehicle-to-vehicle differences are also not addressed.

The occupant's torso transmitted the impact acceleration forces to the neck and head, thus any differences in the response of the ATD's torso and the human subject's torso to the impact forces would affect the head and neck kinematics. Indeed, this appears to have occurred as the human subject's torso appeared to ramp up the seatback while the ATD's did not. The tendency to ramp appears to be related to hip motion as the human's hips appeared to rise a significant amount while ATD's hips did not. The difference in hip motion is probably due to anatomical differences between the human's and the ATD's buttocks. The human buttock is compliant and

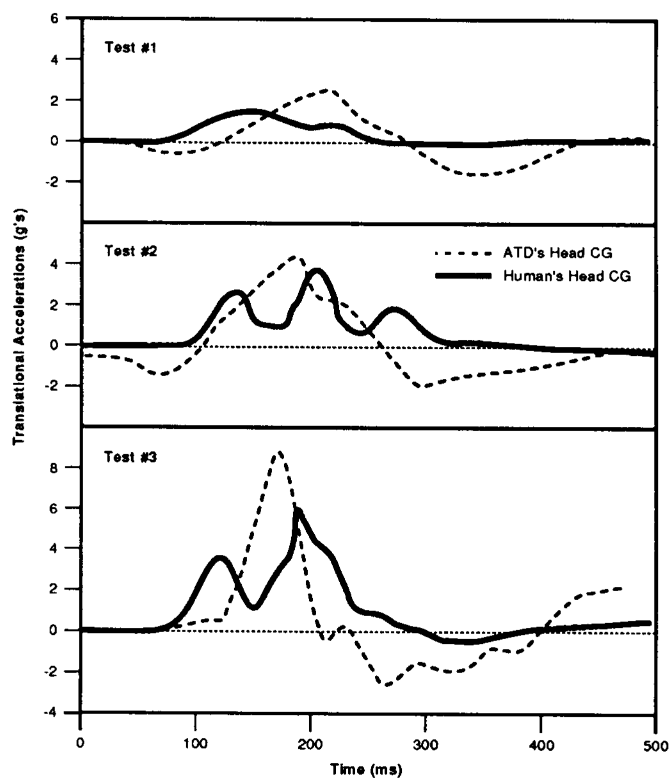

Figure 8. Longitudinal (x-axis) acceleration of the CG of the human's and the ATD's head in the three crash tests.

the hip joint allows the thigh-to-back angle to vary. The Hybrid III's buttock is relatively more rigid and has a fixed thigh-to-back angle. Because of its anatomy, the Hybrid III's buttock probably penetrated into the seatback more than the test subject's, and this engagement prevented it from ramping up the seatback.

It appears that the vertical motion of the human test subject's occipital condyles cannot be fully accounted for by the ramping of the torso and another component of this vertical motion may be the straightening of the test subject's spinal column. The application of a forward force to the subject's back by the seatback would tend to straighten out the normal curvature of the spine, causing the spine to elongate and the top of the cervical spine to rise. Obviously this could not occur in the Hybrid III with its rigid thoracic and lumbar spines.

The resulting vertical motion of the base of the human's neck probably led to compression of the neck during the first half of Phase II. The first acceleration peak for the human's head CG, which is absent in the ATD's curve (See Figure 8), occurred at this time and may be a result of this neck compression, as well as the normal muscle tone in the neck. The neck compression may stiffen the neck with respect to shear forces, thus allowing the neck to transmit x-axis shear forces to the skull and accelerate the skull forward. The second peak seen in the longitudinal acceleration curve for the human's head occurs when the head is in its rear most position relative to the vehicle and is probably due to neck tension forces and any contact forces from the head restraint. The Hybrid III's neck appears to be capable of accelerating its head forward only through tensile forces, thus the single longitudinal acceleration peak when the head is at its most rearward position. If the whiplash injury mechanisms turn out to be related to the forces that generate the forward or vertical translational accelerations, the Hybrid III ATD would appear to be a poor surrogate to evaluate whiplash injury potential in the ΔV range of 4.0 to 8.0 kph.

The Hybrid III also did a poor job of duplicating the rotational motion of the human head. By design the cranio-cervical junction of the Hybrid III allows little rotation in the sagittal plane (rubber stops limit the motion), thus rotation of the head in the sagittal plane has to be done by bending of the neck. On the other hand, the craniocervical junction of the human, the occipital condyle joints, allow approximately 15° of rotation in the sagittal plane (the head "yes" movement). The greater freedom of movement about the occipital condyles allows the human's head to rotate about a point somewhere between the CG of the head and the occipital condyles, while any rotation of the Hybrid III's head in the sagittal plane is mostly due to deformation of the neck. These different mechanisms of head rotation probably explain some of the human and ATD differences seen in the angular displacements (See Figure 6) and angular accelerations (See Figure 7). Of particular significance is the Hybrid III's apparent insensitivity to the ΔV, both in the amplitude of the rearward angular excursion and the rearward and forward rotational accelerations. Since the whiplash injury has some positive correlation with the magnitude of the rearward rotation[2], it appears that the Hybrid III would be a poor human surrogate for predicting whiplash injury, especially at ΔVs in the upper range of those looked at in this test series (6.0 kph to 8.0 kph). If the injury mechanism is found to be related to the head's rotational velocities and accelerations, the Hybrid III also appears to be a poor human surrogate for predicting whiplash injury in the upper end of the crash severity range investigated.

CONCLUSION

The motion of the human head and neck appears to be much more complicated than the Hybrid III's head and neck motions in low-speed rearend impacts, not a surprising finding when one considers the more complex anatomical structure of the human head and neck compared to the Hybrid III's. Preliminary results indicate that the Hybrid III would probably not be a good human surrogate for evaluating whiplash injury potential in low-speed rearend impacts with ΔV's in the range of 4.0 kph to 8.0 kph as the ATD's head and neck kinematics are dissimilar to the human's. A final evaluation of the Hybrid III's whiplash injury predicting capabilities cannot be made until the actual injury mechanism or mechanisms of the whiplash injury are better defined and the ΔV range is extended past 8.0 kph.

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