Human Head and Neck Kinematics After Low Velocity Rear-End Impacts - Understanding "Whiplash"

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ABSTRACT

A second series of low speed rear end crash tests with seven volunteer test subjects have delineated human head/neck dynamics for velocity changes up to 10.9 kph (6.8 mph). Angular and linear sensor data from biteblock arrays were used to compute acceleration resultants for multiple points on the head's sagittal plane. By combining these acceleration fields with film based instantaneous rotation centers, translational and rotational accelerations were defined to form a sequential acceleration history for points on the head. Our findings suggest a mechanism to explain why cervical motion beyond the test subjects' measured voluntary range of motion was never observed in any of a total of 28 human test exposures. Probable "whiplash" injury mechanisms are discussed.

INTRODUCTION

Our first study, done in February 1991 and reported[31] to the SAE in March 1993, involved four test subjects who were exposed to a series of ten low delta-V (4 - 8 kph or 2.5 - 5.0 mph) rear end impacts between standard road vehicles in an approved human test study protocol. Several other studies published since our first presentation have reported similar findings[5,52,55]. Drawing from the practical lessons learned during our first test series, a second test series was conducted in July 1993 utilizing seven test subjects (including three return volunteers from the first series) who represented a somewhat broader age and anthropometric variation range. This paper reports findings from our analysis of their kinematic responses to a test series of fourteen rear end impacts including a higher range of impact related ΔV (5.8 - 10.9 kph or 3.6 - 6.8 mph) than was previously studied. The resulting head, neck and torso kinematics from a total of eighteen human and four Hybrid III anthropometric test device (ATD) exposures were recorded using a variety of improved electronic and high speed film based data collection methods. The resulting data were analyzed with visual graphic methods and with specially developed mathematical techniques to interpret and combine both angular and translational biteblock accelerometer information with digitized high speed film data. With the resulting clearer picture, all but one of our observations from the first article were confirmed, some of our earlier observations and unanswered questions were able to be refined or corrected and a biomechanically rational explanation of human head, neck, torso, seatback and head restraint interaction during rear end collisions can now be offered along with comments suggesting a proposed mechanism of injury related to the often referred to, but ill defined "whiplash" syndrome.

APPARATUS AND TEST SUBJECTS

VEHICLES AND TEST SITE - The total of 14 test-collisions were performed using three vehicles; one vehicle was used primarily as the striking or "bullet" vehicle, leaving the two other vehicles as primary "target" or struck vehicles. The bullet vehicle was a 1984 GMC C-1500 pick-up truck, while the target vehicles consisted of a 1986 Dodge 600 Convertible and a 1984 Buick Regal Limited Coupe. The test site was an unused section of paved road characterized by a very mild slope running downward (approx. 2% grade) in the direction of motion of the vehicles. A ramp inclined at approximately 14° was constructed and used to launch the bullet vehicle to the test protocol's desired impact speed (Figure 1).

Some modifications were made to the test-vehicles for practical and safety reasons. The GMC's front bumper was replaced by a steel reinforced and wood faced structure which better withstood the horizontal impact forces during repeated impacts with the struck cars. Since previous testing had shown that the struck vehicle had acquired most of its velocity change prior to any kinematic response of the occupant, the acceleration pulse shape variation expected because of this bumper modification did not appear to affect our occupant kinematics. Modifications to the struck vehicles included the addition of steel braces which were placed behind the front seats to safeguard against seatback failure. Since safety brace to seat back contact never
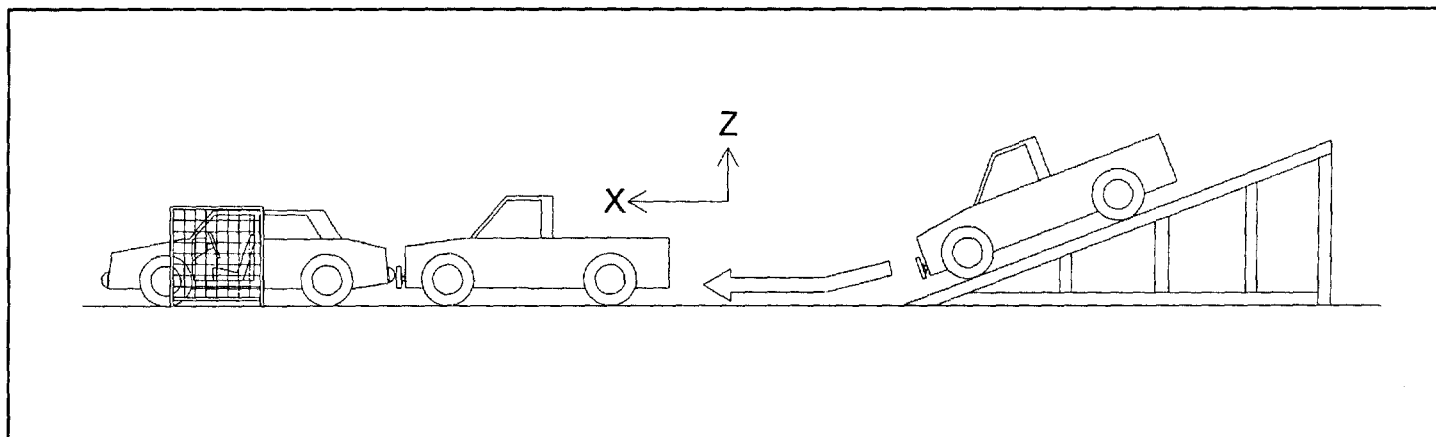
Figure 1 - Test Area and Ramp Setup

occurred during any of the test runs, our safety braces did not influence seat performance or occupant kinematics. Another modification was to remove the front doors of each test vehicle, allowing for better visibility of both the occupant and the seat dynamics. These doors were replaced with frame structures which maintained the rigidity of the vehicles. Factory standard head restraints in both the target vehicles were normally kept in their most fully raised position. In the sedan, where most of the head and neck kinematic data was obtained, the top of the test subjects' head was from 16 to 20 cm. (6.3 to 7.9 inches) above the top of the head restraint and the back of their heads were between 5.1 to 11.7 cm. (2 to 4.6 inches) in front of the head restraint's forward surface. The factory standard 3-point restraint systems were used for each test run with the intentional exception for one test run when both human driver and right front seat passenger were asked not to wear their restraint systems. Each vehicle was inspected after each test run for any safety related problems, as well as any mechanical or impact related changes that might influence test outcomes. Repairs to the vehicles were made as necessary prior to each test run.

TEST SUBJECTS - The test protocol for the current test series was reviewed by the University of Texas Health Science Center Institutional Review Board and IRB Protocol #9010099006 of the University of Texas health Science Center, under DHHS Regulation 46.110(3), approved the use of eight human test subjects selected from the staff of Biodynamic Research Corporation. Seven healthy fully informed volunteer male test subjects, ages from 32 to 59 years, ranging in height and weight from 173 - 188 cm and 76 - 118 kg. (68 - 74 in. and 167 - 260 lb.), completed a pre-testing medical history and physical evaluation, including cervical spine radiographic studies and measurement of each subject's voluntary maximum neck range of motion (extension and flexion) and normal upright head carriage angle.

Test subject marking for photographic analysis included photographically visible marks placed (a) on each individually fitted biteblock and accelerometer assembly, (b) just behind and above the orbital angle of the outboard eye on the skin of the lateral forehead/face, (c) 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 and (d) a "flag" type target affixed to the skin over the spinous prominence of the first thoracic vertebra (T-1), meant to be visible from the side. (Figure 2) Same sized target marks were placed laterally over the outboard glenohumeral joint and elbow on a tight fitting garment worn over the torso and arms. A similar target mounted on a light plastic strip was affixed with Velcro to a tightly fitted corset-like garment worn over the hips and lower abdomen to approximate the lateral projection of the outboard hip joint position. Bilateral foam rubber ear plugs were utilized as additional visual targets and to further mask the already low operating noises from the distant high speed cameras that might alert the test subjects to the exact time of the impact. A Hybrid III anthropomorphic test dummy (ATD) was fitted with a biteblock type accelerometer assembly and had similar right side anatomical reference point markings applied, with the exception of the corset-target strip assembly, ear plugs and the T-1 flag.

INSTRUMENTATION - Fourteen of the eighteen total human test exposures were accomplished with our test subjects instrumented with biteblock accelerometers. (Figure 3) The individually fitted biteblocks required only a minimal amount of bite pressure in order to remain tightly in place during impact. A biteblock typically housed an array of three translational accelerometers (Endevco 7290-10/30) mounted to record x-, y-, and z-accelerations. The x (fore-aft) and z (up-down) accelerations were recorded using 30-G accelerometers, while a 10-G accelerometer measured y (left-right) accelerations. In most cases, biteblocks also accommodated an array of up to three angular accelerometers (ATA ARS-01) sensitive to head angular motions in the pitch, roll and yaw directions (i.e., sagittal, coronal and transverse planes, respectively.) The ATD was, for the most part, instrumented the same as our human test subjects. Four of the human test exposure runs were accomplished with the data acquisition biteblock assembly replaced by specially constructed light weight dental appliances (split biteblocks) that carried two "flag" type photographic targets which were fixed to the subject's upper (maxillary) and lower (mandibular) teeth to assess any

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Figure 2 - Test Subject Instrumentation and Marking

Figure 3 - Transducer Locations

jaw motion.

The electronic instrumentation (ideally 6 transducers per subject) was usually implemented for the drivers and, during the dual position tests, the passenger in the struck car. Additional pairs of accelerometers measuring x- and z-accelerations were mounted onto the central consoles (i.e., near the vehicle's center of gravity) of both the striking and struck vehicles. All transducers were connected to a Bridge Conditioner and Amplifier System (BCAS, Endevco, 68207-6) which was interfaced with a personal computer via an IEEE-488 general purpose bus. All signals were digitized with a data acquisition system board (RC Electronics IS-16E/CR) in the personal computer and were recorded at 2000 samples per second. The data acquisition system was manually triggered a short time before impact. After triggering, data was collected for approximately 1½ seconds and stored in the mass storage media of the computer.

PERIPHERAL DATA ACQUISITION EQUIPMENT - Detailed photographic documentation of test runs was accomplished with four 16-mm high-speed motion picture cameras (two Redlake Fastax and two Photosonics 1B) running at approximately 250 frames per second and equipped with a 100 Hz LED timing light. These long focal length lens cameras were placed during most of the test runs at two fixed positions about 7.6-10.1 m (30-40 ft) from each struck vehicle side and focused to record about the first 183-244 cm. (6-8 ft.) of the occupant's movement. Both the vehicle and the
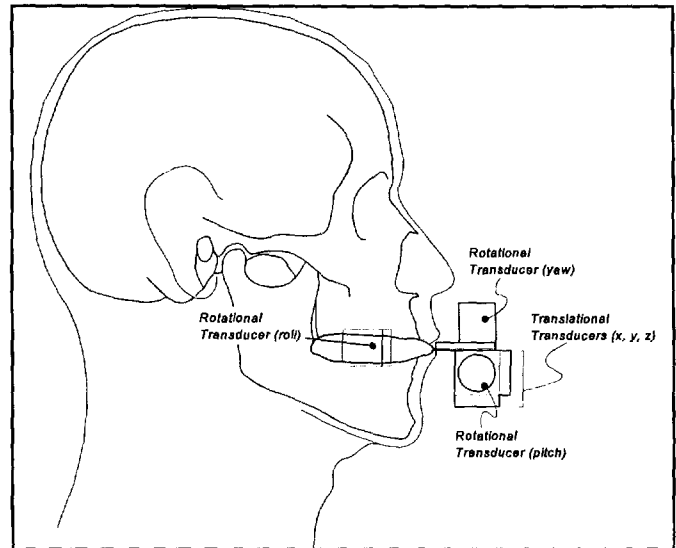
occupants carried target markings which were later digitized frame by frame using a motion analyzer (NAC MOVIAS 160F) to produce position vs. time data. Four standard 8-mm video cameras (Sony EVO-9100) were also used for qualitative documentation of the events. For this test series two free standing photographic grids were constructed consisting of large rectangular frames strung with white cords creating a 15.25 cm (6 inch) square grid system to provide a photographically visible earth fixed reference system. These grids were placed for each test as close as practically possible to each side of the target vehicle.

The closing velocity of the striking vehicle was determined using a speed trap which consisted of a succession of tape switch contacts. In each collision, one wheel of the striking vehicle rolled over the speed trap just prior to making contact with the target vehicle. The electric pulses recorded by the data acquisition system then facilitated the calculation of the closing velocity of the striking vehicle.

In order to coordinate film and transducer data, triggered electronic strobe lights were placed in the field of view of the cameras. These flashed at impact time when the tape switches mounted on the rear bumper of the struck vehicle were compressed. The change in voltage induced by the tape switches was also monitored by a channel on the data acquisition system.

TEST PROCEDURES - Each test run was conducted according to a pre-established test protocol which had scheduled the three day series of human subject test runs planned so each human test subject would have no more than a single daily exposure to a struck vehicle delta-V of 8 kph (5.0 mph) or greater and that each test subject would be exposed to increasing delta-Vs. It had been determined from the first test series, and reconfirmed during the second, that driving the bullet vehicle, even for the higher speed collisions, was not particularly uncomfortable and was unlikely to be injurious. As a result, occupants of the 8 kph and over struck vehicle runs typically might have functioned as a driver of the striking vehicle during other higher

speed runs on the same day. For each test run the striking vehicle was backed up the ramp to a marked position and released with the transmission in neutral and the engine running. It then rolled down the ramp, over a short section of roadway and through the impact point speed trap where the velocity was recorded. This procedure was repeated until the desired pre-determined impact speed was reproducibly achieved. When all was ready, the vehicle to be struck was placed into its stationary position at the impact point and the previously prepared test subjects and/or the ATD were situated in the vehicle and their sensors connected to the recording hardware. The striking vehicle then rolled down the ramp to the impact point. As before, no vehicle control inputs, except for minimal bullet vehicle steering to ensure centerline contact between vehicles, were made during all but one test run. For this particular test the target vehicle driver was instructed to keep the brakes firmly applied during the test. After every test collision, each test subject's physical condition and subjective symptom experience was checked, a post test assessment of vehicle damage was completed, and electronic/photographic test result data storage was accomplished. Daily informal test subject checks were conducted for approximately one month after the test series and then periodically thereafter for long term subjective symptom assessment. All test subjects have remained accessible to follow-up. Data from fourteen manned vehicle to vehicle test collisions were recorded.

COMPUTATIONAL APPROACH

The data output of the second test series yielded two types of computationally useful data; acceleration data obtained from transducers and position/angulation data based on digitized high-speed film.

KINEMATIC ANALYSIS - Since a substantial amount of head rotation and translation in the sagittal plane occurred simultaneously in every test, accelerations at various points on the head of an occupant were not expected to equal accelerations at the biteblock. A goal of this work was therefore to use the information obtained from the biteblock transducers and from digitized high speed film to determine accelerations experienced at other locations on the head of a test subject.

Naming B as an arbitrary location on the head of a subject (Figure 4), an expression for its acceleration was written as follows,

$$\ddot{\boldsymbol{R}}_B = \ddot{\boldsymbol{R}}_{A/B} + \ddot{\boldsymbol{R}}_A \qquad [1]$$

in which the bold type face denotes vector quantities.

In terms of components given in the reference frame of the vehicle we then had,

$$(\ddot{\boldsymbol{R}}_B)_X = -R_{A/B} (\alpha \sin \theta + \omega^2 \cos \theta) + (\ddot{\boldsymbol{R}}_A)_X \qquad [2]$$

$$(\ddot{\boldsymbol{R}}_B)_Z = R_{A/B} (\alpha \cos \theta - \omega^2 \sin \theta) + (\ddot{\boldsymbol{R}}_A)_Z \qquad [3]$$

in which ω and α are the angular velocity and acceleration, respectively, of the link AB (i.e., of the occupant.) The parameter α was obtained directly from angular transducers, ω was obtained after numeric integration of α, and θ was directly derived from film. The second terms in both equations [2] and [3] represented measured accelerations and were thus readily available from translational transducers after the application of a coordinate transformation discussed below.
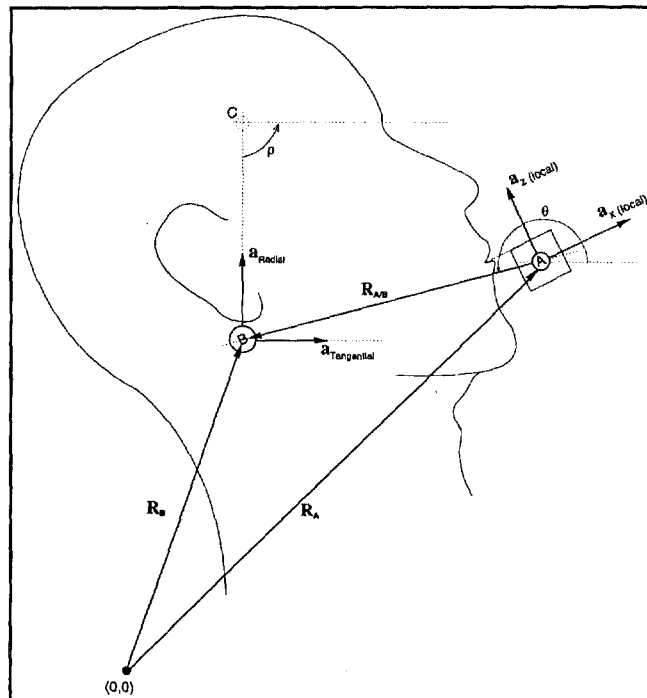

Figure 4 - Calculation Landmarks (nomenclature)

As previously mentioned, measured accelerations (at the biteblock) and computed accelerations (at any other location on the head) encompassed simultaneous translational and rotational effects. Film data became very helpful in the quantification of rotational contributions because it allowed for the computation of the centers of rotation, C, associated with the rotational motion of link AB (i.e., rotational motion of the head). The knowledge of C, whose method of computation is described further below, gave an immediate insight as to the approximate magnitudes of pure rotational effects. Indeed, tangential and radial accelerations for any point were thus available as $r\alpha$ and $r\omega^2$, respectively, where r was the distance from the computed center of rotation to the point of interest.

PREPARATION OF FILM DATA - Film data required considerable preparation before being computationally useful. Film data were digitized using a motion analyzer to yield position data (in terms of digitized units) versus motion picture frame numbers. For every camera view, two points a known distance apart (12" generally) were digitized to provide a scale factor that allowed for the conversion of digitized units into physical displacement units. The 100 Hz LED timing marks appearing alongside the actual footage were digitized as well. Computations based on these digitized

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timing marks provided more accurate frame rates than the stated nominal 250 frames/second rate characteristic to each of our high speed cameras.

The list of position targets that were digitized for each camera view, at a rate of every 2 to 5 film frames, encompassed up to 17 targets (the number of digitized targets varied somewhat depending on the field of view of each camera.) Targets of most interest for this analysis were the Grid Point (GD, a fixed reference point digitized in order to account for film jitter), the Vehicle Point (VH), and, on the head of a test subject, the temple (TM), the earplug (EP), the mastoid (MS), and the biteblock (BB). Also digitized were an upper and lower marker on the seat backrest.

As a result of the head's kinematic response, some of the head targets disappeared momentarily due to obstructions to vision during the motion of the head. MS and EP would typically be briefly concealed by the overlying shoulder harness, for example. Unmanageable high contrast sunlight/shadows would occasionally be a
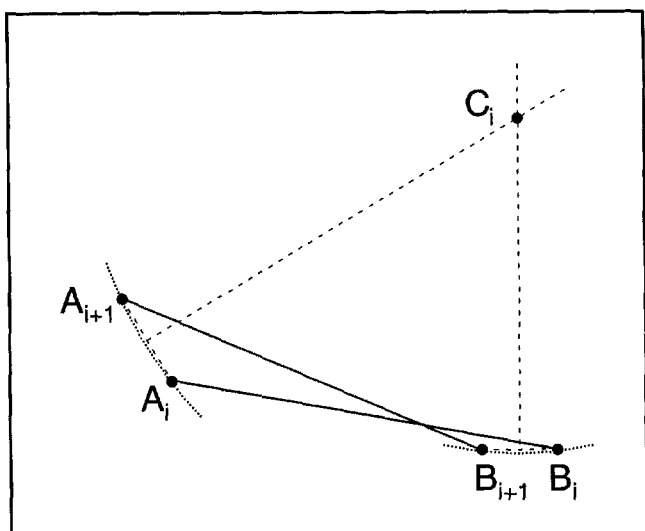
Figure 5 - Center of Rotation Analysis Geometry

problem as well. When such gaps of data were encountered, existing data before and after these gaps were used to create cubic curve fits which, in turn, allowed for the gaps of data to be filled. Once all film data was obtained for every target of interest, the film data was then smoothed with a 2nd order Butterworth filter at 80 Hz break frequency, and splined (with cubics) to transducer data time steps (5 ms.).

PREPARATION OF ACCELEROMETER DATA - Unlike the film data, accelerometer data did not require much post-test computational manipulation aside from filtering and subtracting the gravitational 1 G component. Both rotational and translational accelerometer data were filtered using a low-pass Butterworth filter with cut-off frequency of 80 Hz.

COMPUTATIONS BASED ON FILM DATA - Several parameters were calculated from position data. The angle θ and its numerically differentiated 1st and 2nd derivatives were computed yielding θ_{film}, ω_{film}, and α_{film} values versus time. Secondly, based on the

coordinates of A_i, A_{i+1}, B_i, and B_{+1}, instantaneous centers of rotation C_i were obtained for the motion of link AB (Figure 5). Coordinates of C_i were determined by solving for the intersection of two lines; one line being the mid-length perpendicular of the line defined by $[A_i, A_{i+1}]$, and the other line being the mid-length perpendicular of the line defined by $[B_i, B_{i+1}]$. Clearly, the locating of C_i was a task that was very sensitive to small angle variations in the two lines expected to intersect. This is the reason why position data were fitted with smooth and continuous cubic functions.

$$a_X = a_x \cos \phi - a_z \sin \phi \qquad [4]$$

$$a_Z = a_x \sin \phi + a_z \cos \phi \qquad [5]$$

COORDINATE FRAMES OF REFERENCE - Transducer accelerations were naturally obtained in the reference frame of the moving head. For consistency, all acceleration data were eventually transformed to an earth orthogonal reference frame using the coordinate transformation calculation given below, where ϕ is an angle describing the orientation of a body with respect to the horizontal plane and lower case subscripts represent a local reference frame. In this work ϕ would generally be replaced by θ if dealing with total acceleration or by ρ if dealing with centrifugal or tangential accelerations.

FILTERING - Transducer acceleration data (both angular and translational) were filtered using a 2nd order Butterworth filter with an 80 Hz cut-off frequency. Position data were also smoothed using a 2nd order Butterworth filter. Another type of filter that proved to be useful was the ATM (Alpha Trimmed Mean) filter. It was helpful because derivatives of angular film data frequently produced jagged results which were efficiently smoothed using the ATM filter without affecting existing smooth sections.

CUSTOM SOFTWARE AND SYNCHRONIZATION OF DATA - A C++ program which included an ATM filter and a polynomial curve fitting procedure, was written to help in carrying out the present analysis. After entering data from test run files holding digitized timing marks, filtered position data vs. frame numbers, and the filtered accelerometer data vs. time, this program provided many of the results that were sought and allowed for the proper synchronization of film and transducer data.

Every run of the program handled acceleration and position data for two targets at a time, providing, as a part of the output, acceleration data associated with those two targets. Most commonly, out of the two targets analyzed, one target would be the one at which the transducers were located (i.e., point A in Figure 4). Based on the knowledge of the accelerations that had occurred at the biteblock target (point A), accelerations at the other target were then automatically computed. An additional option in the program allowed the user to request acceleration data at any point on the sagittal plane of the head other than the two original targets. The location of this new point simply had to be defined

with respect to the two original targets in terms of a distance and an angle.

RESULTS AND FINDINGS

Data from each run consisted of medical history and observations obtained before and after each test exposure, the raw electronic biteblock and vehicle accelerometer data and the high-speed film/video record. The use of angular accelerometers on the biteblock arrays increased the information available and considerably facilitated the accuracy of the photographically visible test analysis. The photographically visible test subject marking system and high speed photography was greatly improved from the first test series and the addition of the earth fixed visible grid system permitted better qualitative and quantitative assessment of test subject displacement-time information down to 4 millisecond intervals.

COMPUTATIONAL RESULTS - Listed in Appendix A are sample angular data (Figs. A1 and A2) and acceleration data (Figs. A3, A4 and A5). Transducer and film angular data were compared in order to assess the synchronization of the two sources of data. Proper synchronization was important because both the angle θ, and center of rotation computation were based on film data.

The computed time varied centers of rotation were found to match well with the simultaneous apparent centers of rotation observed on film. Examples of these are shown in the sample vector plots included in Appendix Figs. A4 and A5. This match was valid from impact time to approximately 150 msec after impact, at which time the then substantial translation of the head/neck complex lessened the accuracy of the center of rotation analysis. Up to approximate 150 msec after impact it was possible to evaluate contributions of rotational effects at any point in the sagittal plane of the head, particularly at the Mastoid point which typically experienced the higher accelerations. The tangential acceleration was found to typically reach values exceeding 10 G's during the period prior to 150 msec after impact. This appeared to account for a significant proportion of the acceleration values experienced at the Mastoid point.

TEST RELATED CLINICAL FINDINGS - The human exposure portion of this test series was accomplished during a consecutive three day period. (See Table 1.) Four test subjects were exposed to three test runs each, one test subject had four test exposures and two subjects were exposed only once. The single test exposure for the two test subjects was due to their limited time availability. The same limitation prevented the eighth test candidate's participation in the test series. Four individuals on the approved test panel had participated in the first series of rear end collision tests completed almost 2.5 years before the current test series. These individuals reported having had no testing related interval symptoms. Three of these prior test participants continued to have normal cervical radiographic studies and the fourth, who had minimal

cervical degenerative changes on his first cervical radiographs was found to have had no perceptible progression of those findings on his second set of x-rays. All of the new test participants had normal cervical spine x-rays and reported no underlying health problems. One of the new test subjects did report in his pre-test interview being slightly prone to heightened muscle tension associated with vigorous physical activity or stress. Test related symptoms reported by the test subjects are summarized in Table 1. All test subjects reported some test related "awareness" or discomfort symptoms, however slight and/or fleeting. Fleeting headaches reported by Szabo[52], et al, were also noted by most of our test subjects. Those test subjects who were multiply exposed during the three day period noted that their early, just noticeable symptoms, became more pronounced as their test exposures continued. Test subject #2 was the individual who reported increased muscle tension with stress and injury and was the one who participated in the two leftward turned head (30 and 45 degrees) off center line test runs (Table 1). After his third test run and his second turned head test run, he developed somewhat more significant discomfort symptoms than his peers and was not permitted to participate further. His first exposure was with a 30 degree left head turn at a delta-V of 5.8 kph (3.6 mph) and his assessment the day after was that he had not been made uncomfortable at all by this exposure. The next day he underwent a 10.0 kph (6.2 mph) head straight exposure early in the day and later reported the onset of a mild frontal headache. His third exposure and his second test run late on day 2 was with a 45 degree left head turn and a delta-V of 8.2 kph (5.1 mph). This was reported to be a subjectively much more stressfulexposure. He developed an uncomfortable, predominantly right sided, anterior and posterior lower neck muscle strain later that evening and was asked not to participate on day 3 of the test series. Test subject #2 was clearly the most symptomatic of the test panel subjects. His discomfort symptoms steadily cleared over 3-4 days after the test series. All other test subjects reported themselves completely symptom free before or during the third day after the test series was completed. In general, our test subjects reported two types of neck discomfort symptom patterns. Most subjects, 4 of 7, reported either upper or lower anterior neck strap muscle discomfort symptoms. Two subjects reported their discomfort symptoms occurred at the posterior base of their necks. The test subject exposed to the off centerline testing reported both types of discomfort. In the two years that have passed between the tests and the writing of this report none of the subjects have reported any symptoms referable to their test exposures.

CHRONOLOGY OF KINEMATIC EVENTS - Our first paper[31] established a convenient five phase description of the occupant kinematics of the low velocity (range 4-8 kph) rear end collisions that were investigated. These phases were termed:

Table 1. Struck Vehicle Test Subject Clinical Symptoms

Test #	Delta-V kph (mph)	Day #	Test Subject Driver	Symptoms (Driver)	Test Subject Passenger	Symptoms (Passenger)
1 Cnv	10.3 (6.4)	1	#1 *	Supernuchal (occipital) H/A, onset 30 min., lasted 45 min.	—	
2 Sed	5.8 (3.6)	1	#2 (Head left at 30°)	Slight "twinge" upper right trapezius muscle, onset about 45 min., lasted 5 min.	—	
3 Cnv	8.0 (5.0)	1	#3 *	"Sensation" at base of neck post impact, left immediately, minor H/A onset 708 hours, lasted until aspirin after 10 hours.		
4 Cnv	8.0 (5.0)	1	#4 *	Transient H/A after head restraint strike, lasted 10 min.	—	
5 Sed	7.7 (4.8)	1	#5 (no restr)	"Awareness" of posterior neck base, onset few minutes, lasted 12 hours.	#6 (no restr)	Mild neck "awareness", onset few min., lasted few hours.
6 Sed	10.0 (6.2)	2	#2	Mild frontal H/A, onset few minutes, lasted overnight.	ATD	
7 Sed	9.2 (5.7)	2	#7	Mild neck awareness, onset few min., lasted few hours.	#3	Dull H/A from head restraint strike, gone in few seconds, 1-2 hours later, mild frontal H/A, lasted few hours.
8 Sed	10.0 (6.2)	2	#1	Lower anterior strap muscle soreness, onset noted just before test, lasted after next test.	ATD	
9 Sed	8.9 (5.5)	2	#5	Increased low posterior neck (C-7) mild discomfort, onset few min., lasted until next test. Later in evening neck was less stiff and discomfort decreased.	#4	H/A, occipital & Rt. retro-orbital, onset at impact, lasted 4 hours, soreness upper SCM muscles, onset 16 hours, lasted 2-3 days.
10 Sed	8.2 (5.1)	2	#2 (Head left at 45°)	Left frontal H/A & occipital soreness, onset in few minutes, discomfort in anterior strap & lower posterior muscles, onset 15 hours, lasted 3-4 days.	—	
11 Cnv	8.0 (5.0)	2	#3 (Brakes set)	H/A & residual neck extension soreness in lateral posterior muscles, onset 15 hours, lasted one day.	—	
12 Sed	8.7 (5.4)	3	#5	Frontal H/A, onset few min., lasted 5 min. Continued low posterior neck mild discomfort, at (C6-7), pre-existing, lasted about 3 days.	#4	Soreness anterior strap muscles, pre-existing, lasted 1-2 more days.
13 Sed	10.9 (6.8)	3	#3	None reported.	ATD	
14 Sed	10.9 (6.8)	3	#1	Lower anterior strap muscle soreness, lasted approximately 2 days after last test.	ATD	

Legend: Cnv = Convertible   Sed = Sedan   (no restr) = no restraint system used   * = split upper & lower bite blocks

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Phase 1 - Initial Response (0 to 100 milliseconds)

Phase 2 - Principal Forward Acceleration (100 to 200 milliseconds)

Phase 3 - Head Overspeed/Torso Recovery (200 to 300 milliseconds)

Phase 4 - Head Deceleration/Torso Rest (300 to 400 milliseconds)

Phase 5 - Restitution Phase (400 to 600 milliseconds)

Our experience during the current test series found the five phase description still valid and convenient. However, one of the principal objectives of the second test series was to extend the experimental range of delta-V above 8 kph (5 mph) to the 11.0 kph (7 mph) level, as well as to investigate in more detail the biomechanically important second and third phases. The improvement in data collected and the higher collision velocities experienced during these tests have further clarified some important areas necessary to understanding a very complex biomechanical event as it evolves over an increasing energy spectrum.

There are several observations that became clear after analyzing the new data. The test subjects' absolute vertical motion with relation to the earth that was reported to have occurred during the first test series was not observed with the higher speeds and better earth fixed reference point visualization of the second test series. At delta-Vs over 8 kph (5 mph), there was very little or no absolute upward body translation with respect to the earth. The relative vertical motion of the test subject's upper trunk and torso ("ramping") with respect to the vehicle seat back, however, was clearly accentuated at the greater speeds of the second test series. This pronounced upward ramping over the seatback of each subject greatly affected their subsequent head and neck kinematics. When the calculated data was reviewed in 2.5 or 4 millisecond intervals there were considerable variations in the resultant acceleration directions of the top of the cervical spine from instant-to-instant between test subjects. However, when all of the test subject's kinematic responses were reviewed as a whole, there was a commonality of response that is summarized as follows. Figures 6 and 7 are provided with trace lines from TM, MS and BB to highlight the observed sequencing of rotary and translational motions for a typical test (Test Run #9). Figure 8 diagramatically represents the principle features of the typical kinematic sequences we observed.

PHASE 1 (0-100 milliseconds) - For all test subjects there was no detectable body motion for at least 50 to 60 milliseconds after the bumper sensors indicated contact between striking and struck vehicles. The struck test vehicle, seat and base of the seat back moved forward about 6.4-7.6 cm. (2.5-3 in.) in this interval and the seat back deflected rearward an average

of 3-5 degrees. Due to the rearward slope of the forward moving seat bottom there was an apparent illusion of hip and thigh elevation with respect to the seat. When hip and pelvis are tracked with respect to the earth fixed grid it was clear that hip and thigh stay stationary while the sloped seat moved out from under, causing the low back area to contact and compress the seatback at a point somewhat higher than if the individual were more slowly slid rearward over the sloping seat bottom.. As this happens, the test subject's pelvis and low back area compressed, and became braced by, the low seat back cushion and started deflecting the entire seat back rearward and relatively away from the still stationary torso. Between 60 and 80 milliseconds the vehicle and seat base moved to about 10.2 cm. (4 in) and the seat back deflected rearward a total of about 6-7 degrees. During this period the initially stationary upper body was pulled forward from below by the pelvis and the lower portion of the trunk intersected the increasing rearward slope of the seat back. The net result of the torso staying vertically stationary as it laid back on the forward moving, rearward deflecting, and therefore vertically lowering seat back was a 5-8 cm. (2-3 in.) ramping up of the shoulders and upper thoracic spine (T-1) over the seat back incline. (Figures 6 & 7.) The mid-back then began intersecting the forward moving seat back surface. As it was pushed forward the thoracic curve became straightened out, further increasing the ramping effect. By 80 milliseconds the test subject's T-1 target flag had moved forward about 2.54 cm. (1 in.).

During this period the head had not moved at all, although the base of the neck had also moved forward along with T-1. The normal neck muscle tone that keeps the head erect was now exerting a forward pull to the top of the neck and thus the neck's attachment to the head. (Figure 9) From about 80 milliseconds onward the forward accelerative forces at the top of the neck built rapidly. By 100 milliseconds T-1 and the base of the neck moved forward another 1-2 cm. and the top of the neck had just begun to move.
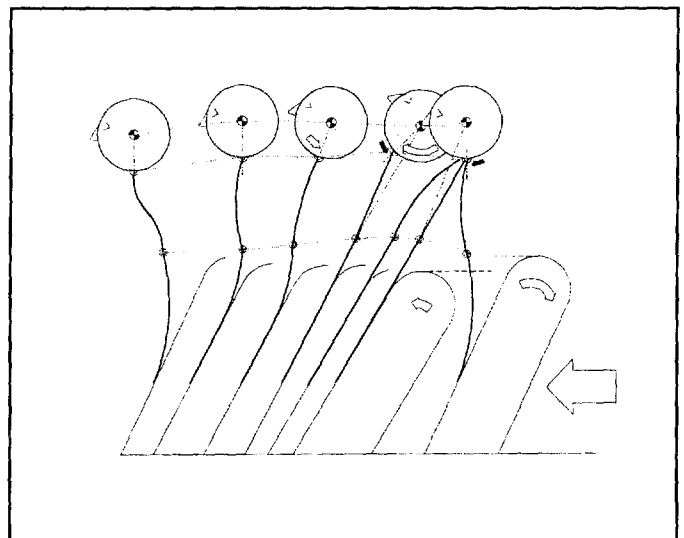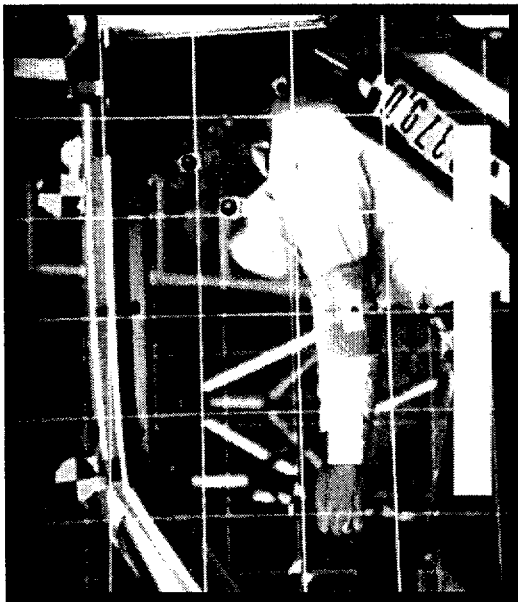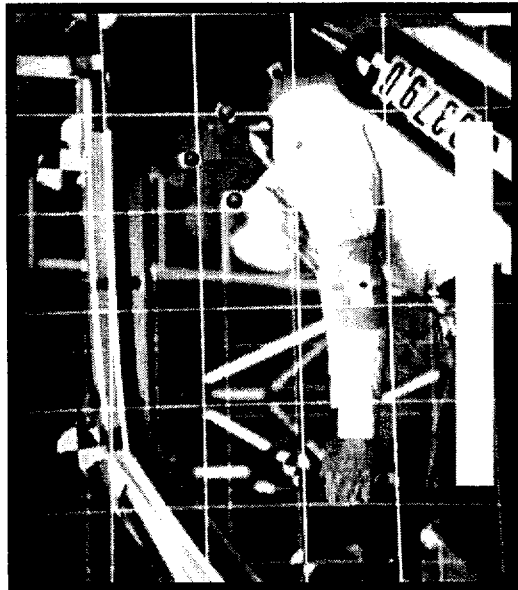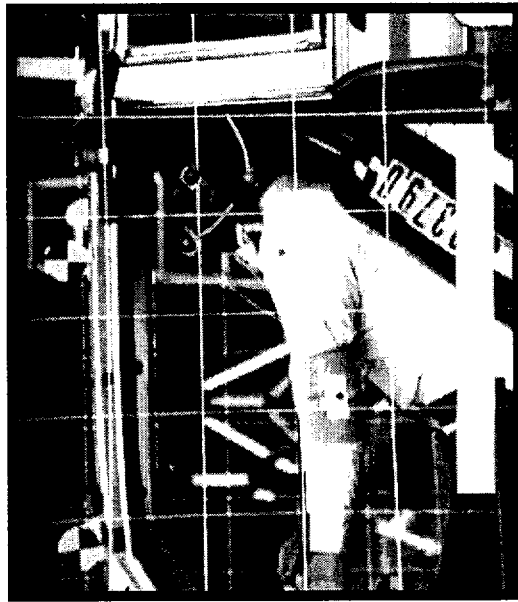

Figure 8 - Kinematic Response Diagram

222

100 ms

152 ms

84 ms

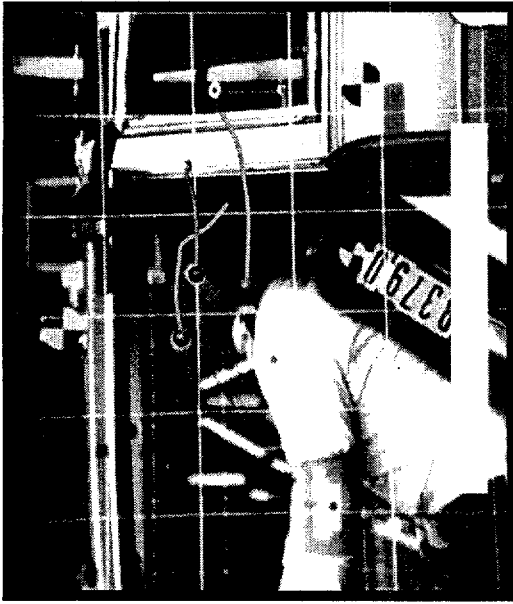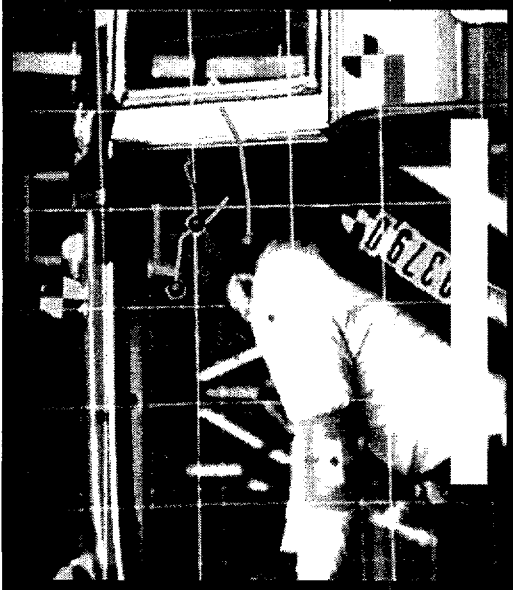132 ms

0 ms
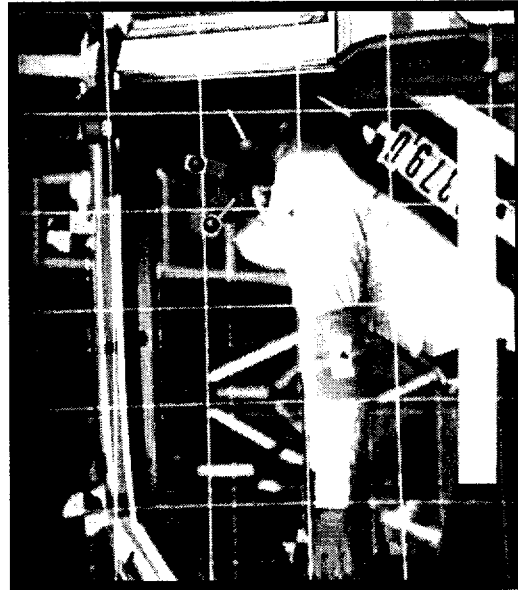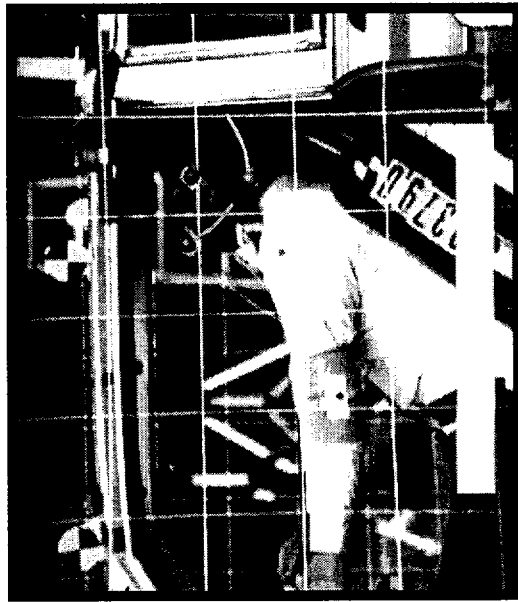
116 ms

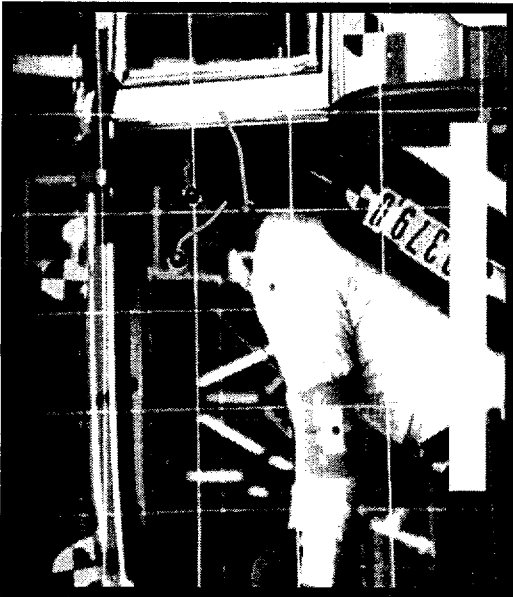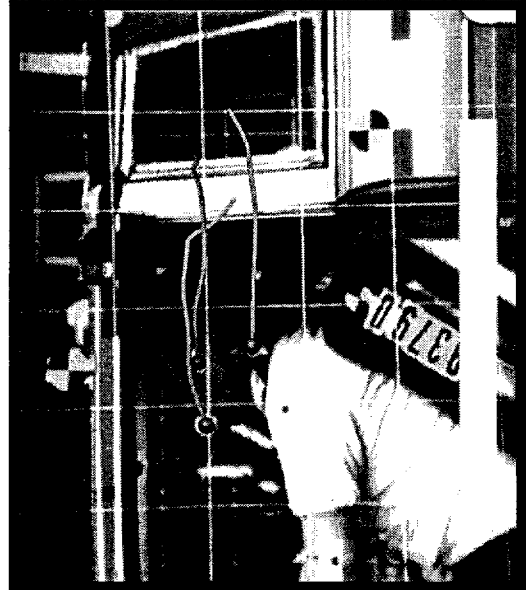Figure 6: Typical Head/Neck Kinematics

196 ms

260 ms

180 ms
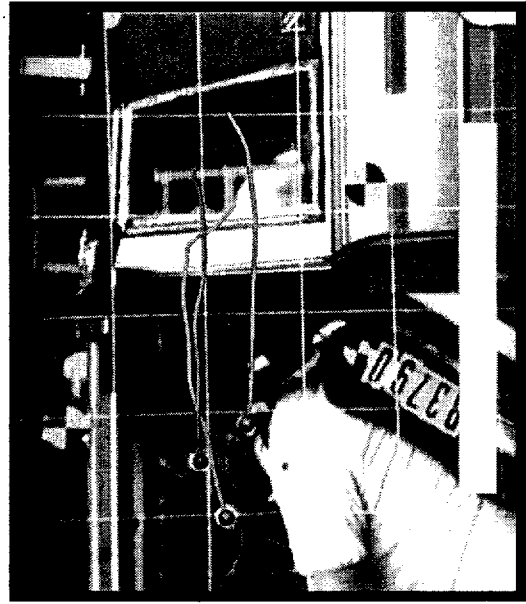
228 ms

Figure 7: Typical Head/Neck Kinematics

164 ms

212 ms

224
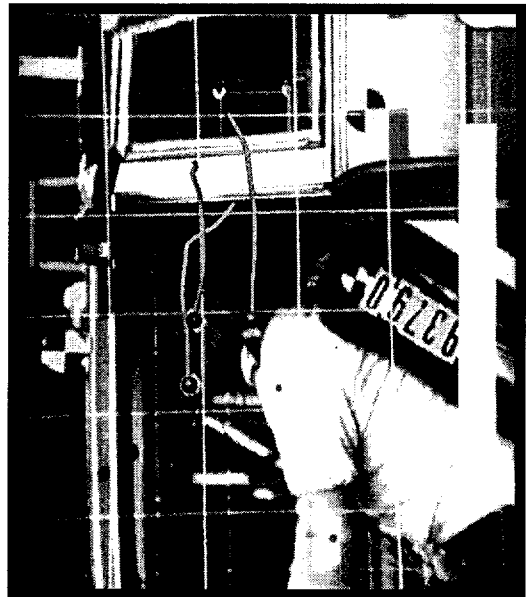
PHASE 2 (100-200 milliseconds) - By 110 - 120 milliseconds the seat back had reached its maximum rearward deflection of 10-14 degrees. (Note. The convertible had a more compliant seat back than the sedan and had a higher maximum deflection by about 2 degrees) and the typical test subject reached a maximum top of the neck (mastoid point) acceleration (5 - 15 G). The vehicle had traveled forward about 15.2 - 17.8 cm. (6 - 7 in.) and T-1 moved forward about 8 - 10.2 cm. (3 - 4 in.) The neck still appeared oriented almost vertically at this point. Instances were clearly observable on the high speed film of several test subject's sternocleidomastoid (SCM) muscles visibly bulging under their skin in response to the abrupt loading of a functioning muscle group. This early head motion appeared to be entirely rotational, about a point within the head which was probably close to the head and neck complex's center of gravity. The most apt analogy to the human head and neck at this point is the response of a heavy ball and chain to a pull on the chain tangential to the chain's attachment to the ball. Between about 110 and 170 milliseconds the head rotated about 10 - 15 degrees and then started to translate forward under the impetus of the neck top's continued forward motion. Around 180 - 200 milliseconds the typical test subject's head reached its maximum rearward rotation and maximum neck extension of 18 - 51 degrees. Taller subjects tended to peak 10 - 30 milliseconds later. All of test subject 3, contacted the fully elevated head restraint on the top surface with their lower occipital scalp in a downward direction. This resulted in the head restraints being driven downward on their adjustable mountings on every run over 8 kph. (Note. Test subject 3, who had the shortest seated height of the test panel appeared to have more quickly contacted the upper portion of the front surface of the head restraint and
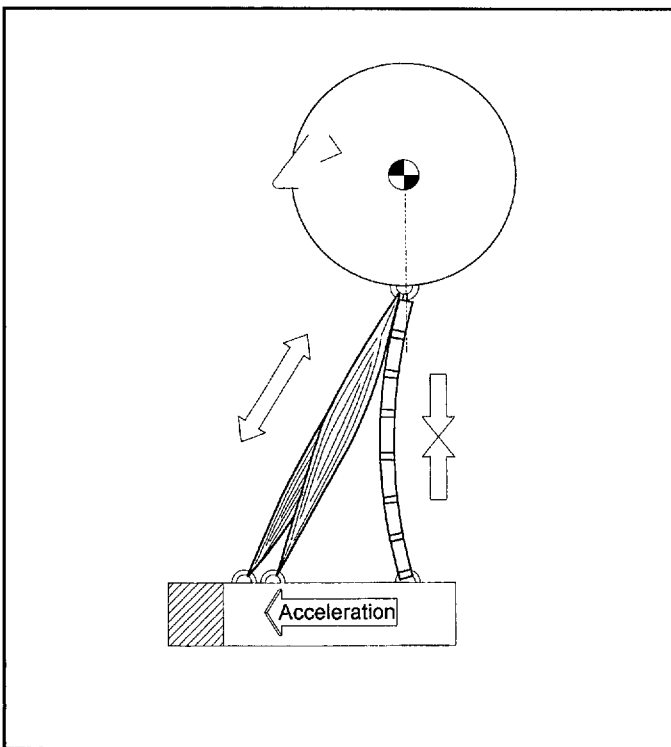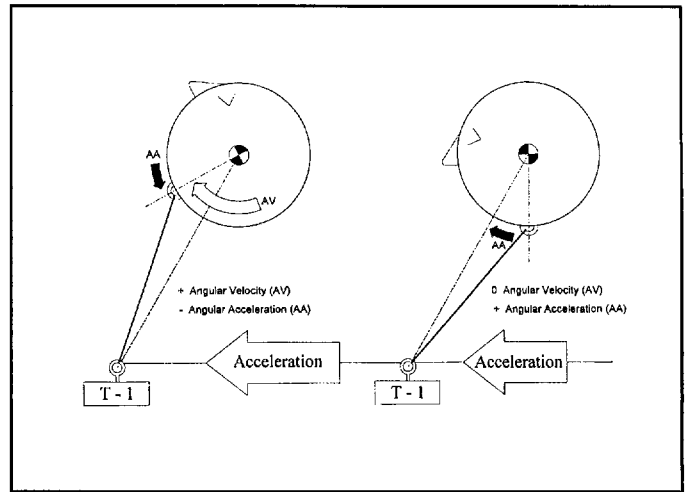

Figure 10 - Ball and Chain Analogy

higher on his occipital scalp than did his peers.) At 180 - 200 milliseconds the seat back deflection and therefore the torso and T-1 angle had decreased to about 5-6 degrees as its work of accelerating the torso was being accomplished. The maximum head angle achieved minus the increase in torso rearward extension gave a good approximation of the actual maximum neck extension during the test exposure. All subjects had less neck extension than their maximum voluntary neck extension as recorded prior to testing by about 10-40 degrees. (Note. Test subject 3 intersected the head restraint prior to achieving the same rotation as his peers and achieved a higher margin of unused extension capability. The rest of the test subjects had a 10-14 degree margin.) For test subjects other than number 3, the head restraint by itself did not appear to significantly arrest the rearward rotation of the test subject's head since these particular head restraints moved relatively easily downward in their adjustment pathways. The ball and chain analogy (Figure 10) offers a likely mechanism for the observed self limitation of the head's rearward rotation and neck extension at this point. As the base of the neck continued to be accelerated forward there was traction of the top of the neck and at the point of the neck's attachment to the head. The further the head rotated the occipital condyles forward and up, the greater the resistance from C-1 which was being pulled down and forward.

PHASE 3 (200-300 milliseconds) - Early during this period the seat back began to return to its pre-impact angle and the seat cushion to its normal configuration. The torso had just about achieved the vehicle's velocity or slightly greater, regained its normal forward curve and moved relatively downward with respect to the seat back. The head, early in this periodhad achieved a somewhat greater velocity than the torso and, with measured decelerations of 1.5-2.5 G, was actively being slowed down by the neck. During this period active control of the head's position appeared to be regained as the head was starting to approach the "over the top" position at about the 280-320 millisecond point.

Figure 9 - Head and Neck "Tripod"

PHASE 4 (300-400 milliseconds) - The head continued forward relatively faster than the shoulders but was being decelerated in a level, eyes fixed and focused fashion. Previously described in the first report was a "level head bob" maneuver in which the upper portion of the neck extends and the lower neck flexes while slowing the head. Torso and lower body began to achieve their post impact rest positions during this period.

PHASE 5 (400-600 milliseconds) - By this time the test subject had, just about totally achieved the vehicle's impact related velocity change and was returning to his pre-impact position. The slightly higher positioning of the trunk and hips from the pretest position was an unanswered question from the first paper that may be explained by the seat slope derived "landing" of the pelvis and low back area higher up the seat back as described in the above Phase 1 kinematics description.

DISCUSSION

The unique kinematic patterns associated with human test subjects exposed to low velocity rear end collisions shown by this study, while difficult to completely describe in print, are readily apparent when shown in a slow motion format. This is particularly true when the whole photographic record of the test series is viewed back to back as many times as necessary and the associated moment-to-moment G forces of selected anatomical points are available. Key points of this pattern begin with the initial absolutely fixed body position while the vehicle and seat assembly move forward. The seat back impinges forward onto the lower body and responds to the load of accelerating the lower body by deflecting rearward away from the upper torso. When the seat back swings rearward in the vehicle, the seat back top and head restraint are lowered with respect to the still stationary torso, which is met by the forward moving (in earth based coordinates) seat back at a point on the seat back higher than was true in the pre-collision rest position. Added to this ramping motion is the acceleration related uncoiling of the thoracic curve, resulting in the T-1 mounting point for the neck rising quite a bit higher up the plane of the seat back. The head remains stationary during this period, but, due to the falling position of the head restraint, appears to "loop over" the advancing and lowering head restraint. Seated height appears important with taller people contacting the head restraint more on the top surface and shorter people striking more on the forward face of the head restraint. These stature differences result in qualitative differences readily visible to the eye, but difficult to point out and characterize in the calculated data. Figures 11 and 12 graphically show the time history of calculated instantaneous acceleration vectors of a family of points located over the sagital plane of the head. The first major acceleration of the head is angular with the initial 10 - 15 degrees about a nearly stationary point of rotation. Here at about 110 - 120 milliseconds, typically lasting for a period less than 15 - 20 milliseconds, is where the highest mastoid point accelerations (5 - 15 G) were computed. The neck is still almost fully erect at this time and is beginning to show indications of muscular resistance to what is then a transverse acceleration for the still "stiff" head and neck column complex.

Head rotation begins to become apparent after about 100 to 130 milliseconds and then blends with the onset of an increasing forward translation of the entire head. The head's rearward rotation begins to slow as first the ball and chain effect operates and then the overspeed of the head in relation to the top of the torso reverses the head rotation at about 180 - 200 milliseconds. A total rearward head rotation of up to approximately 50 degrees occurs over 60 - 90 milliseconds and then reverses over a longer rebound period. The rearward deflecting seat and the uncurving of the thoracic spine allows considerable rearward angulation of T-1, lessening the extension of the neck required by the head/neck's apparently self-limited rotation/extension. Much of the forward translational acceleration of the head takes place during the subsequent period between 120 to 200 milliseconds, although there are portions of the head's mass below the apparent center of rotation that become accelerated in the forward direction during the rotational period.

Because the head and neck have continued to rotate during this period the translational acceleration vector becomes more in line with the neck's rearward curving longitudinal axis and at much lower (perhaps 2 - 4 G) average force levels than the initially experienced mastoid point accelerations of 5 - 15 G's produced during the primarily rotational phase of head motion.

It must be pointed out that these 5 - 15 G values are calculated for a single reference point undergoing an arcing motion (hence a mostly tangential acceleration) about a center of rotation that is located higher and more forward than the mastoid point and the head's center of gravity. Although calculated G-loadings at the mastoid were noticeably higher during the primarily rotational motion of the head, it is important to note that the early rotational kinetic energies ($\frac{1}{2}I\omega^2$) imparted to the head invariably reached levels about five to six times lower than translational kinetic energies imparted to the head ($\frac{1}{2}mv^2$). Therefore, from the standpoint of actual neck loading (and injury potential), the force needed to produce the observed mastoid tangential acceleration during the early period required less neck loading than would occur if the same magnitude of translational acceleration were produced at the head's center of gravity.

Our preliminary assessment of the translational G forces experienced at the head's center of gravity show a range of about 3 - 6 peak forward G's. Subsequent to these events the rebounding seat back and recoiling torso result in a rapid retreat of the shoulders and T-1 down parallel with the seat back surface, resulting in a vigorous motion of the torso downward and forward with respect to the vehicle.
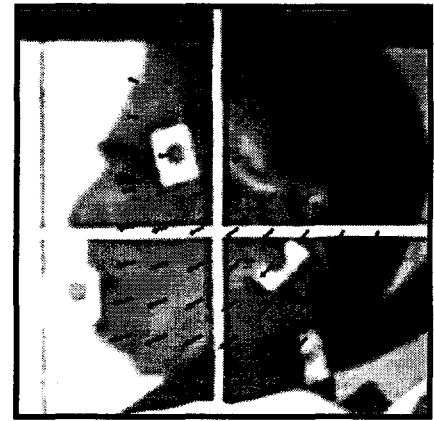
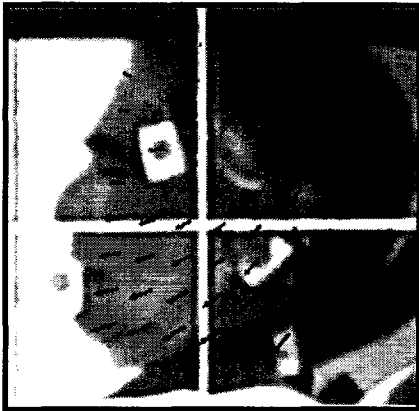It was noted earlier that several special test variations were instituted to answer some of the
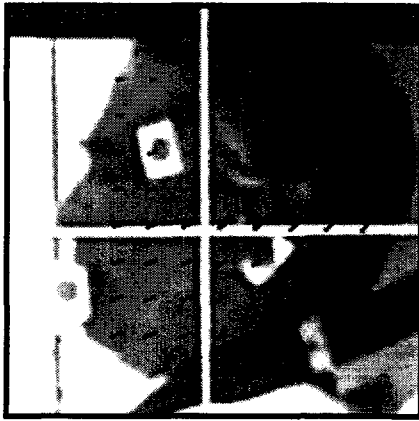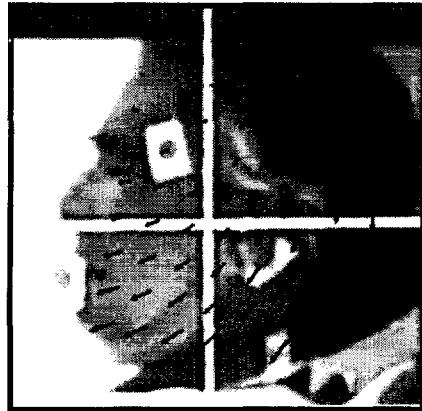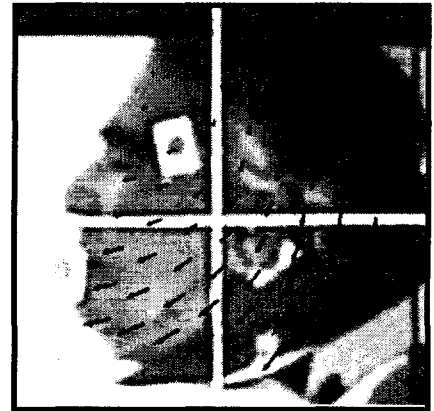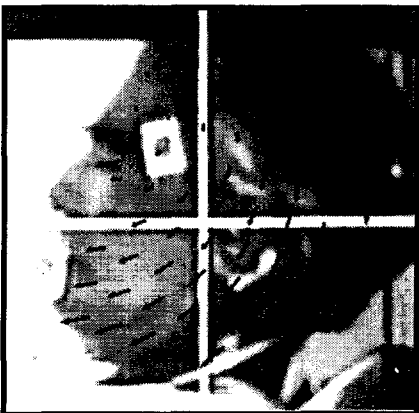
106 ms   110 ms   114 ms
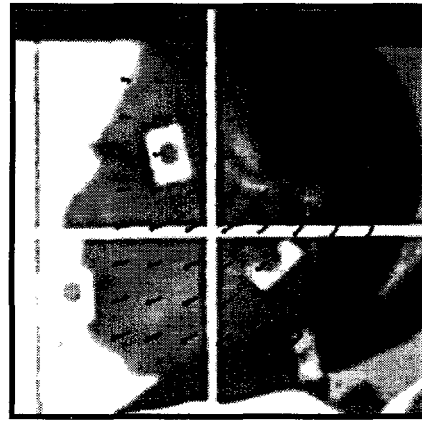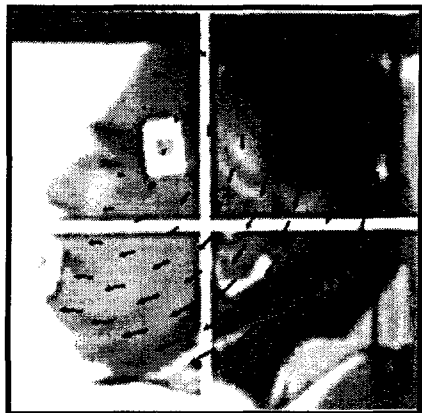
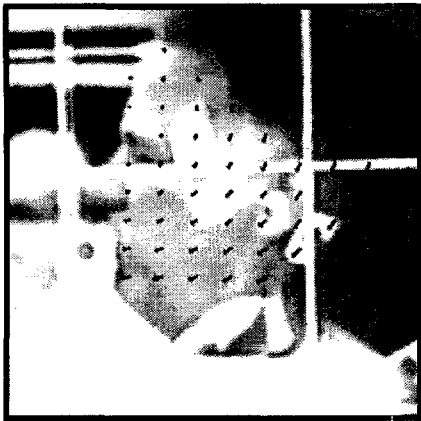118 ms   122 ms   126 ms

130 ms   134 ms   138 ms
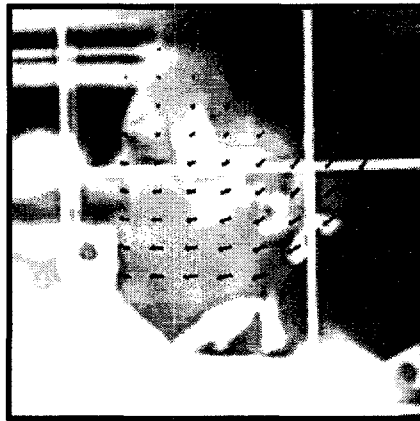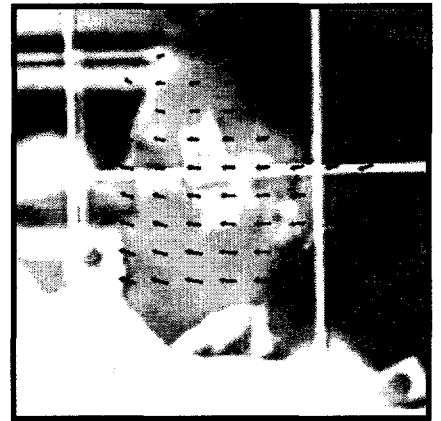
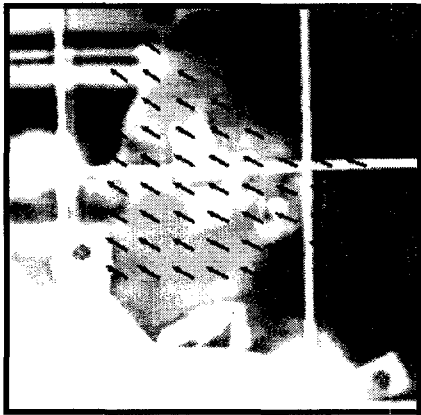Figure 11: Test 7 Acceleration Vector Fields
(See appendix figure A.5 for vector scale)

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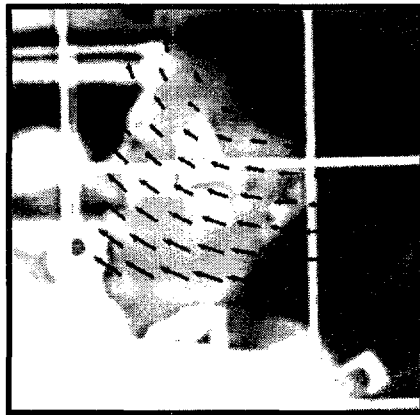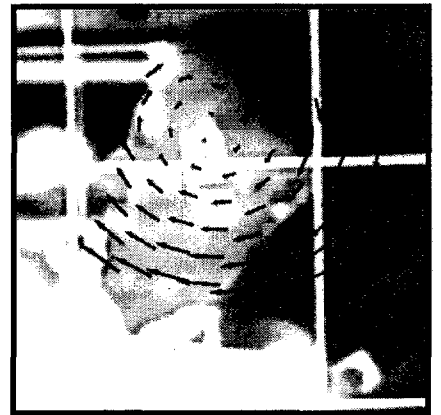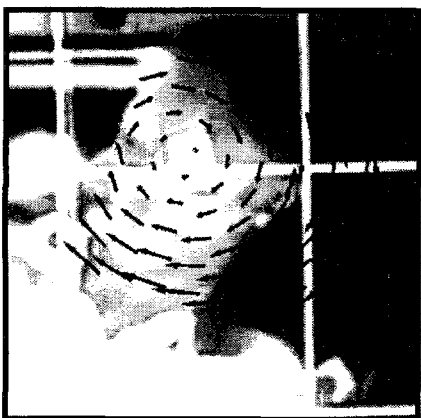94 ms   98 ms   102 ms

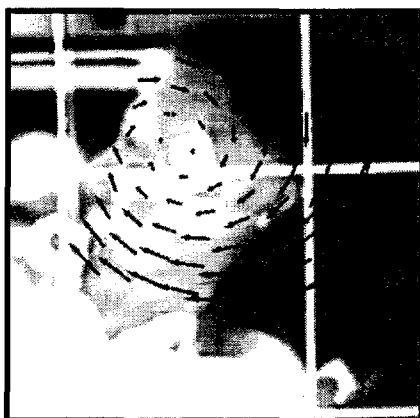110 ms   114 ms   118 ms

122 ms   126 ms   130 ms

Figure 12: Test 12 Acceleration Vector Fields
(See appendix figure A.4 for vector scale)

questions raised by our earlier test series. Two test subjects on one test run did not use their restraint system. There were no apparent significant qualitative or quantitative differences in their kinematic responses when compared to other test runs. It appears that restraint system use may not play a significant role in this type of low velocity event. The results of the off center line tests have been detailed above. It appears that muscular strain injury potential may be moderately increased for individuals in some low velocity rear end collisions if their heads are significantly turned. The split biteblock tests for tracking jaw motion are the subject of another investigation to be reported later.

Based on these observations, noting that the greatest accelerations occurred while the neck was upright, that muscular resistance was demonstrably occurring during this time period and the fact that our repetitively exposed test subject's symptoms support the assumption of either an acute, mild strain injury to anterior and posterior neck musculature or perhaps mild compressive irritation to vertebral structures in the base of the neck, it seems reasonable to believe our test related neck injuries must have occurred very early in our test subject's kinematic response to the experimental collisions. If this is so, a proposed mechanism for injury is illustrated by Figure 9. At rest in driving position, the head might be considered to be a ball-like mass which must be actively controlled by neck muscles with some degree of constant contraction to keep the head stable against gravity and whatever miscellaneous movements that might be occurring. The anterior neck strap muscles and the two SCM muscles can be thought of as forming the front two legs of a three legged structure, with the cervical spine forming the rear leg. At 90 - 110 milliseconds the base of this system has moved forward while the mass of the head lags behind. To accelerate the head the front two legs of the tripod (composed of partially contracted "toned" muscle) must be in tension and the rear leg (the cervical vertebrae) must be in some compression. The analog of this situation is the individual who, while carrying a moderate weight in his arms, unexpectedly has a very heavy weight added suddenly to his load. Acute biceps muscle strain is the likely result. It is also conceivable that mild acute compressive irritation of some of the more sensitive structures could occur in the posterior parts of the compressed and partially extended spinal leg of the tripod, most likely in the posterolateral facet joint columns and/or spinous processes.

CONCLUSIONS

The better detailed and more extensive data from this second test series permits refinement of some of the conclusions about occupant kinematics presented previously for a broader, more energetic range of rear-end collisions and a greater number and anthropomorphic variety of test subjects. The absolute Gz accelerations with reference to the earth's orthogonal frame of reference were not as significant as expected from our previous work, however, the Gz forces experienced by our test subjects with reference to their ramping interaction with the vehicle seats and seat backs were perhaps more significant than previously anticipated. The relative lack of human test subject low back differential motion, as it becomes quickly braced by the advancing seat back, makes any injury to this area quite unlikely as a result of a low velocity rear end collision. The early first motion of the human head is primarily rotational, blending into rotational and increasingly translational motion with a mechanism that seems to self-limit and then correct the rearward head rotation and neck extension. Not only was there no cervical hyperextension occurring in any test subject, there was a substantial margin of physiologic neck extension left at the point of maximum rotation achieved during each test, well before any of the test subjects would have reached their normal voluntary maximum extension limits. Since all of our test subjects, particularly the multiply exposed ones, developed some form of typical "whiplash" symptoms, it seems reasonable to finally conclude that hyperextension was not the cause of their symptoms. The observed early peak accelerations at 110 - 120 milliseconds, while the neck is still mostly erect and resisting principally transverse forces suggests that this is most likely when muscle strain and possibly compressive irritation may occur. After this period, forces on the neck begin to return to those experienced during day to day activity levels. If that is true, then standard design automobile head restraints, while still very valuable, are in the wrong position to mitigate low velocity neck injuries of this type. These acute neck strain injuries would have already occurred before a passive "head catcher" could intervene. Flexible seat backs appear to be a more effective mechanism to decrease the magnitude of kinematic neck extension during these low velocity events, but still can't be fully protective for this type of injury and also must remain stiff enough to handle the more serious high speed rear end collision. After our present experience with a higher energy test series, 8 kph (5 mph) still seems to be a convenient ΔV threshold for assessing injury potential. For events progressively below this level, the acute muscle strain injury likelihood decreases, probably quite rapidly, even for "thin necked" people. For single events above this level the likelihood of transient acute neck and shoulder muscle strain injury and possible mild compressive irritation of the posterior neck may increase. Several of our test subjects have accumulated 6 - 8 significant (above 8 kph or 5 mph) rear-end collision exposures, without the subsequent development of any persistent cervical symptoms of any kind. As this is written it has been more than four years since the first test series and over two years since the second test series. After analyzing both of our test series there were no observed biomechanical events that could have resulted in permanent cervical injury, and there have been no subsequent indications of any persistent "soft tissue injury" symptoms by any of our test subjects.

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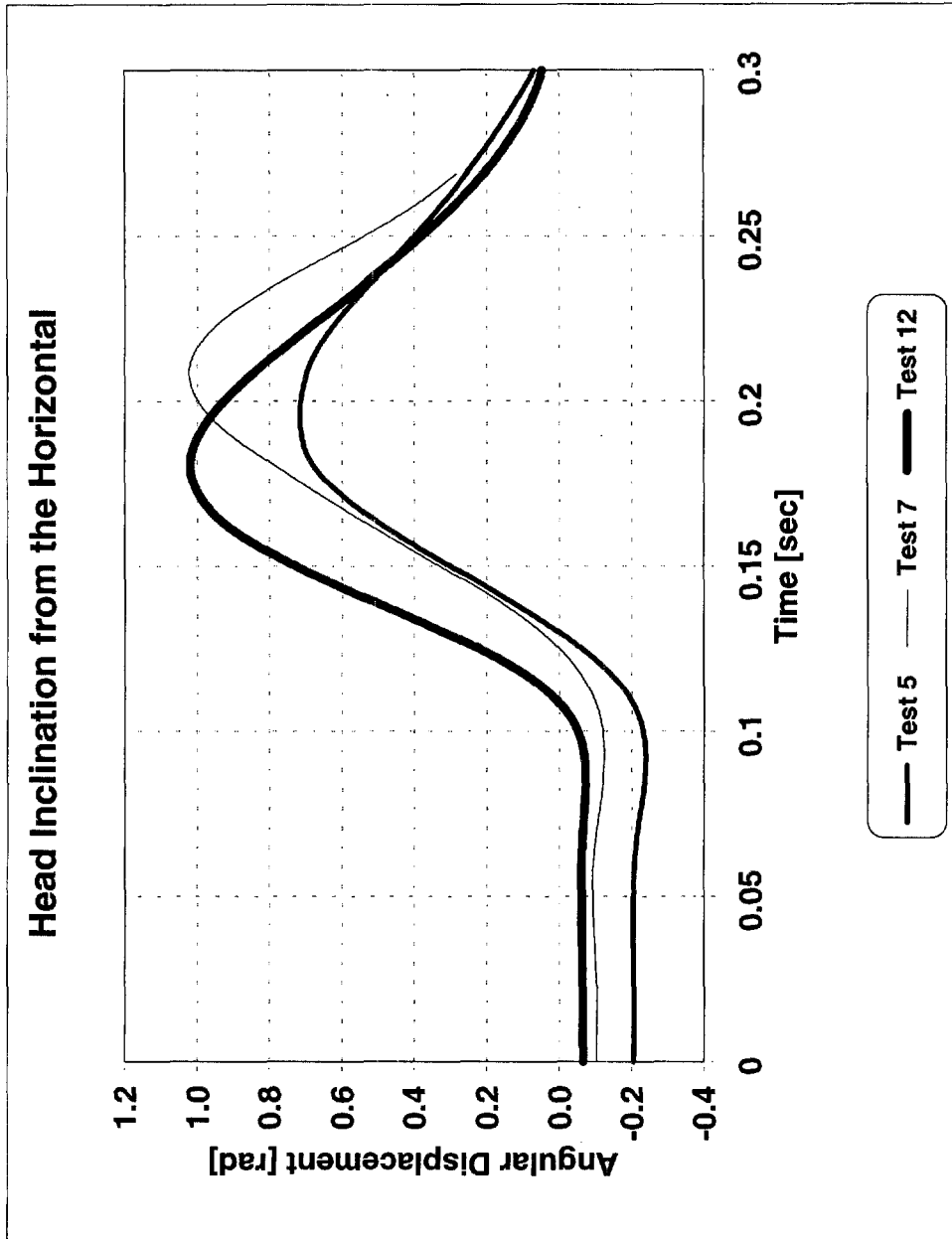   1993 May/June; pp. 22-26

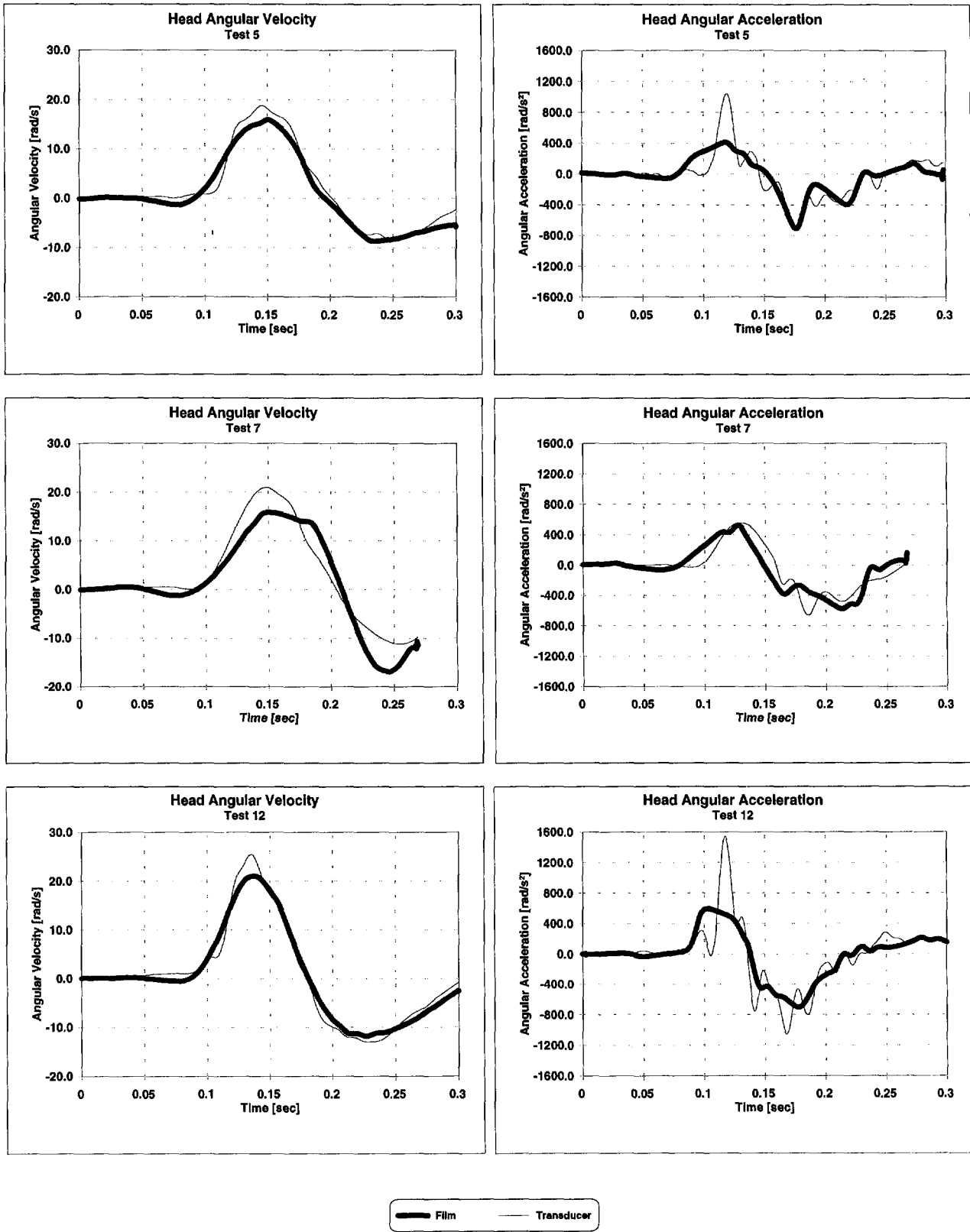Figure A.1. Head inclination with respect to the horizontal

Figure A.2. Head angular velocities and accelerations as measured with transducers and from digitized film.
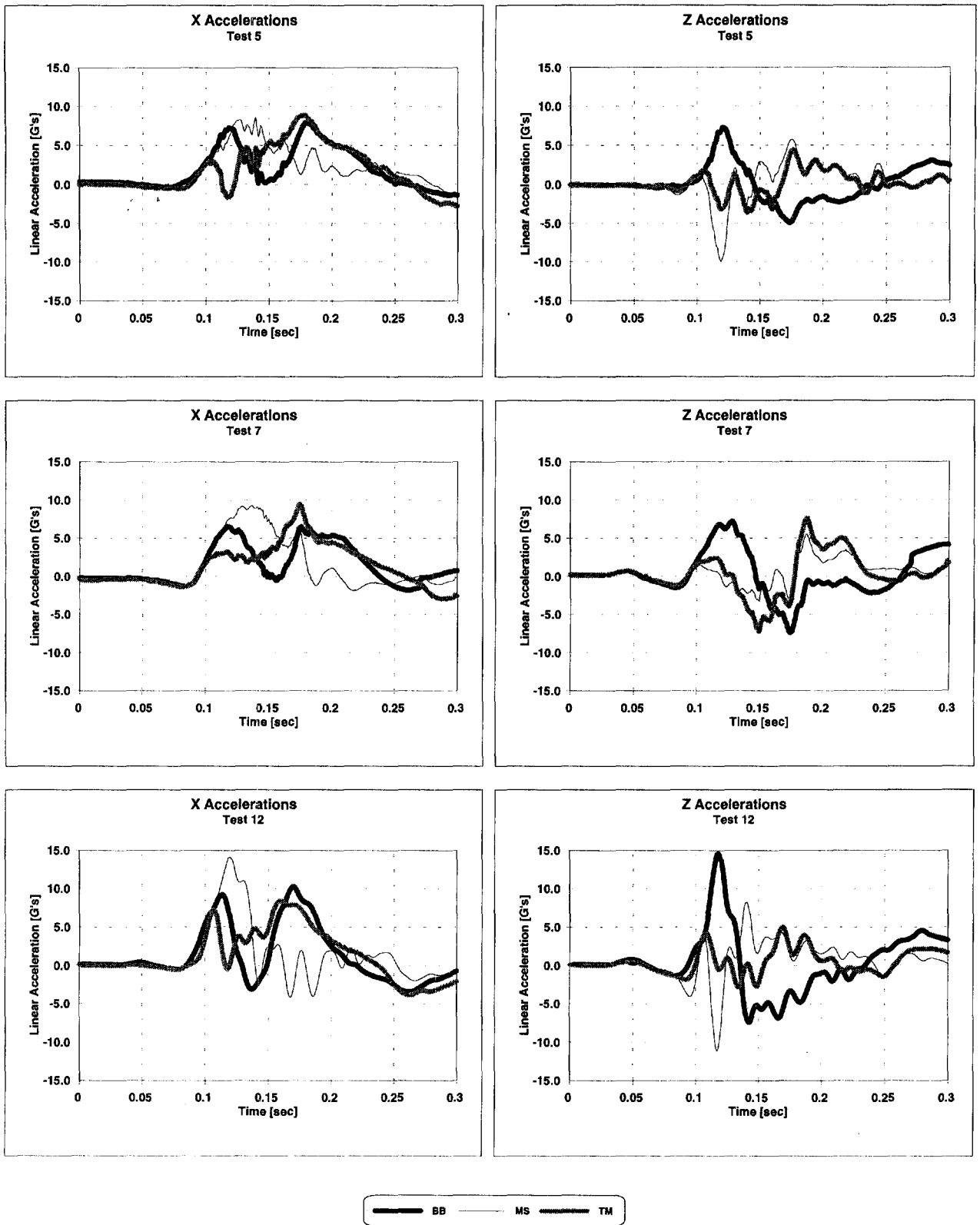
Figure A.3. Acceleration at the digitized locations in the head sagittal plane.
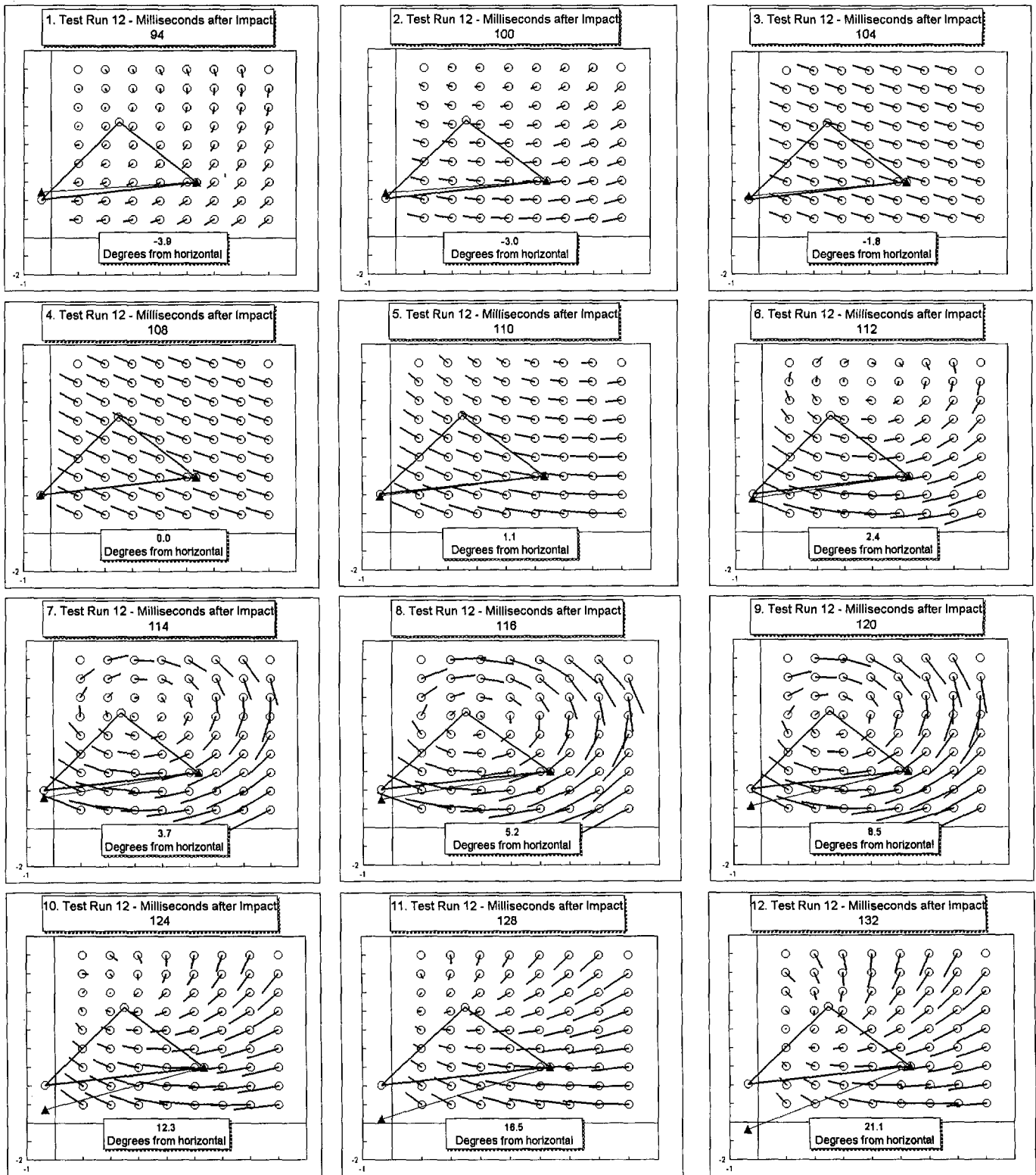
Fig. A4. Acceleration Vector Fields Using 70 Points on the Head Sagittal Plane
Test 12 - Solid Triangles connected by light line is the horizontal plane.
- Dark Lines Connect BB, TM and MS points [open circles].
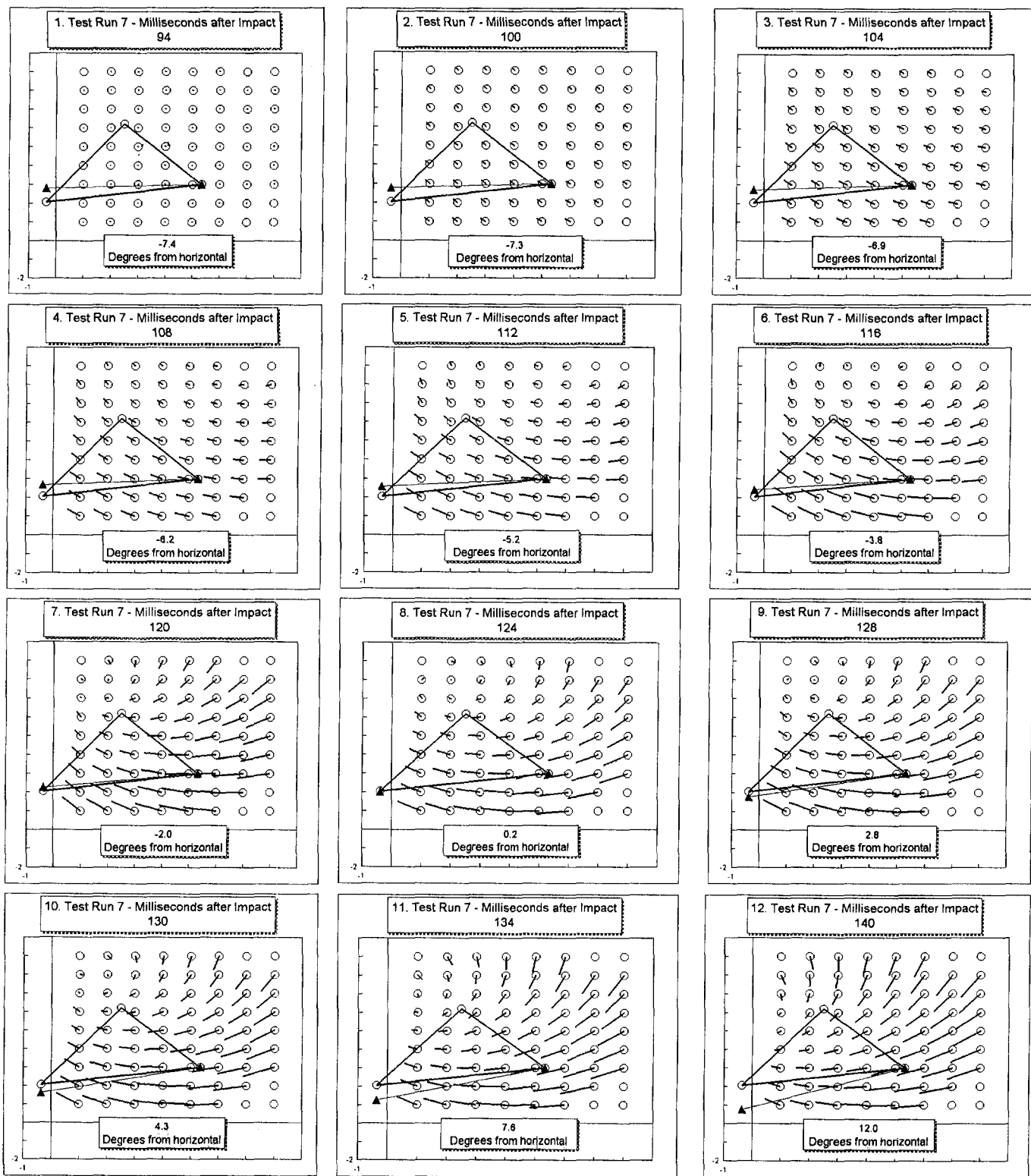- Circles around points of origin represent about 2 "G" vector length.

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Fig. A5. Acceleration Vector Fields Using 66 Points on the Head Sagittal Plane
Test 7 - Solid Triangles connected by light line is the horizontal plane.
- Dark Lines Connect BB, TM and MS points [open circles].
- Circles around points of origin represent about 2 "G" vector length.

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