A STUDY OF HEAD AND NECK INJURY MECHANISIMS BY RECONSTRUCTION OF AUTOMOBILE ACCIDENTS

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ABSTRACT:

This report presents the methodology and first results of an in-depth study on head and neck injury mechanisms in victims of traffic accidents. Medical data on these injuries were obtained in detail from patients whose accidents were simultaneously studied by an accident investigation team, thus enabling satisfactory correlation between the biomedical and the biomechanical facts in a prospectively designed investigation. The kinematics and body responses of the accident victims were estimated by the application of the Crash Victim Simulator - Three Dimensional Model (CVS-3D). Results of the simulation indicate that the CVS-3D model provides excellent insight into the kinematics of occupants during crashes. Calculated values of head linear and angular accelerations were in the range expected and the ability to calculate neck forces and moments significantly adds to the understanding of neck injury mechanisims in accident victims.

INTRODUCTION

Although there have been many studies on head and neck injury mechanisms utilizing animal and physical models, specific studies aimed at the quantitative reconstruction of human accidents have been difficult to do and few in number. (1, 2)

In order to better understand how serious injuries occur in automobile crash victims, the National Highway Traffic Safety Administration has initiated a detailed study of serious accident cases in the vicinity of Washington D.C. This study, done in conjunction with the Washington Hospital Center, documents the occupant injuries, the vehicle damage and the accident scene data. These data can be used to reconstruct the accident either experimentally or analytically to provide an estimate of the time history of forces, accelerations, velocities and displacements which were associated with the injury.

The purpose of this paper is to present our methodology and summarize the analytical reconstruction of several accidents selected from the Washington Hospital Center Accident Data. In each case, the accident victim suffered either head or neck injuries or both. Each accident was reconstructed using the three-dimensional Crash Victim Simulation Model (3DCVS), developed by the National Highway Traffic Safety Administration (3).

METHODOLOGY

In order to ensure maximum data retrieval our accident investigations were initiated by a telephone call to an Accident Investigation Team (AIT) from the Washington Hospital Center (WHC) Trauma Unit when a suitable head/neck injured victim of a traffic accident was received. This dedicated AIT could thus arrive at the accident scene without too great a lapse of time between the time of the accident, the time of arrival of the victim (or victims) at the Trauma Unit and the commencement of data gathering from the crash site. Following the admission of the patient, the medical team would record the injury data to the victims in a serial manner while the AIT personnel would begin their data collection from the scene of the accident. The severity of each crash was estimated through use of the Crash III accident reconstruction program which estimates the velocity change of the vehicle from damage measurements (4). Monthly data reviews conducted by both AIT and WHC staff enabled retention or rejection of cases for accident reconstruction. To date we have completed the basic biomechanical and biomedical data collection in 84 cases selected from over 200 patients. The basis for these decisions will be published in a forth coming paper (13).

We plan to reconstruct as many of these cases as is possible using the CVS-3D model. This model provides a three-dimensional simulation of the kinematics of the human body during a crash, and computes the forces acting on each vehicle surface and can also provide the linear and angular velocities, accelerations, and displacements associated with each body segment. The data required to operate the model include the acceleration of the vehicle during the crash, the vehicle interior geometry, the engineering properties of the vehicle interior components, the initial position of the human occupant, and the geometry and properties of the human body.

The force-deflection characteristics of the interior components of selected automobiles are being determined in a parallel experimental program (5,6). To date the test program has completed testing of 18 vehicles. The tests include static tests of knees into dashboard, head into windshield, and dashboard, and chest into dashboard. Tests of selected steering wheels/columns have, also, been conducted. These tests include hub crush, wheel crush, radial rim deformation, paraxial rim deformation. The static test data is supplemented by dynamic tests of selected windshields, dashboards and steering assemblies. The details of these tests and the resulting input data sets for computer models will be reported when the test program is completed.

The occupant models being used are based upon the 50th percentile male models reported in references 3 and 7. These occupant models can be adjusted to more closely simulate the size and mass of the actual occupant being simulated. In addition, occupant models have been modified to permit the calculation of neck forces and moments, by using additional dummy segments as described in reference (8).

The neck forces and moments are calculated at the head to neck joint, (head/neck junction) which approximates the location of the neck transducer in the Hybrid III dummy.

A major problem with past attempts to reconstruct occupant impact has been the lack of vehicle component load-deflection characteristics. To date, the vehicle component test program has produced sufficient data so that estimates of the properties of interior vehicle surfaces can be made. In many instances, data is now available on the same make of vehicle as the one being simulated. The occupant models have been extensively used and have been validated to simulate dummy kinematics. Some differences between the simulated and actual kinematics can be expected due to the differences between dummy and human characteristics. However, for primary impacts and injuries which occur early in the simulation, these differences are minimized. The head/neck injury event frequently occurs during the initial body to vehicle contact, and consequently is a good candidate for simulation.

The neck load transducer which has been incorporated in the dummy models has not been validated. Nevertheless, the calculated neck forces and torques will be presented to show the comparative levels for the cases simulated. The presented neck load data is for the contact events which caused a loading duration of at least three milliseconds.

RESULTS

Three cases will be reviewed. Case 1 was a serious neck flexion/compression injury caused by facial contact with the steering rim. Case 2 was another serious neck extension injury complicated by a head injury caused by head impact with the header and windshield. Case 3 had a head injury without associated neck injury caused by impact with the windshield.

Summary of Accident Case 1. Neck Injury

The accident victim was an unbelted driver of a 1982 compact stationwagon who was involved in a frontal impact with a pole. (Case number 153-05 0784; simulation LB01). The occupant was a 28 year old male, approximately 5'7" feet tall and weighing 160 lbs. There was no measurable blood alcohol.

The vehicle sustained a maximum crush of 25". The velocity change was estimated to be approximately 26 mph, based upon a computer reconstruction using the crash program (4). The direction of primary force was estimated to be between-5 to-15 degrees.

A schematic drawing of the interior damage is shown in Figure 1A. The evidence of interior body contacts included oily transfers on the windshield from head and arm contact, and deformed lower dashboard panel from knee contact. The steering column stroked approximately 1 centimeter. It may be noted from the vehicle interior damage that the occupant moved forward and to his left.

Case 1 Occupant Injuries

The head/neck injuries to the victim and the computed values of acceleration are shown Table I. The severities of the injuries are rated by the Abbreviated Injury Scale (AIS) which ranges from 0 to 6, with the higher numbers assigned to injuries with the highest probability of threat to life (9). The most severe injury was focal damage to the cervical spinal cord clinically localized at the C.5/6 level without associated evidence of damage to the cervical spine bony/articular structures. The resultant complete quadriplegia led to an AIS=5 assignment for this injury. The injury sources were upper steering rim and windshield which was contacted by the chin and head and the steering hub and lower rim which were contacted by the chest and abdomen as the occupant moved forward. The occupant's lower face contacted the upper left quadrant of the steering wheel rim causing a laceration (3cm) of the lower lip and fracture of the right upper incisor as his tooth penetrated the lower lip to strike the wheel rim. The chest suffered a minor contusion only, and there were no abdominal injuries. Thus the steering wheel was the cause of the injuries, three of which were minor (lip, tooth and chest) and one critical, to the cervical spinal cord. The facial contact to the steering wheel deflected the occupant's head down and to the left resulting in a head contact with the windshield leaving a 5cm wide by 7cm high oily transfer to the glass. His right hand also struck the windshield leaving oily finger prints but neither head or hand impacts caused significant damage to either the windshield or to the occupant.

Analytical Reconstruction Case 1

The predicted kinematics of the occupant impact are shown in Figures 1.B through 1.G. Figure 1.B. shows the assumed initial position of the occupant. It is assumed that the occupant reached forward with his right arm to cushion the blow, Figure 1.C. shows the occupant 60 ms after the beginning of the impact. Figure 1.D. shows the occupant at 80 ms with the right arm contacting the windshield. Figure 1.E. shows the occupant at 100 ms. At this point in time, the lower face has contacted the steering rim and the chest and abdomen are contacting the hub and lower rim. The left leg is constrained somewhat by the wheel well, thereby contributing to unequal penetration of the knees into the lower dashboard. Figure 1.F. shows the occupant at 110 ms. During the period between 96 and 116 ms the maximum head and neck loading occur. Maximum acceleration on the head were approximately 100G linear and 6300 rad/sec^2 angular. The neck torque rose to a value above 68 Nm for the duration of the period. The maximum torque of 113 Nm occurred at approximately 110 ms. During the period of maximum neck torque the maximum shear and axial loads for 3 ms intervals were 1500 and 4200 N respectively. Figure 1.G. shows the occupant at 120 ms. In this position, the forward velocity has been arrested, and the occupant is beginning to move rearward and to his left. The HIC value for the impact was approximately 330, which occurred between 105 and 123 ms. The head impact and neck loading data for this case are summarized in Table I and II.

Summary of Accident Case 2 Head and Neck Injury

The accident victim was an unbelted right front passenger of a 1983 mid size sedan, involved in a frontal impact (case 12-FDAA-67; Simulation CC00). She was a 34 year old female approximately 5'6" tall and weighing 135 lbs. Blood alcohol level was 0.263. The right front part of the case vehicle struck the rear of a stopped truck causing a maximum crush of 18 inches. The velocity change was estimated to be approximately 18 mph, based upon a computer reconstruction using the crash program. The direction of primary force was estimated at between $+10^{o}$ and $+15^{o}$. A sketch of the internal damage is shown in Figure 2.A. The evidence of interior contacts included the following: Oily and tissue transfers on sunvisor from head contact; tissue transfer and glass damage from head to windshield contact; scuffs and damage to instrument panel and dashboard from chest contact; scuffs and dents in lower dash from knee contacts.

Case 2 Occupant Injuries

The case vehicle's frontal plane was deflected at an angle of 10 to 15 degrees relative to normal by the underriding impact with the truck. The seated victim moved forward and to her right, relative to the vehicle. The left knee contacted the lower dashboard approximately 10cm from center. The right knee contacted the glove box door approximately 33cm from the centerline. These contacts produced only minor abrasions. The victim's head struck the forward edge of the sunvisor compressing it onto the windshield header and leaving oil and tissue transfers on the sunvisor. This head impact caused an abrasion of the forehead. There was no residual deformation of the sunvisor or header. Although the head motion forward was thus partially arrested, the torso continued to move forward, causing a significant loading of the neck resulting in a subluxation of the cervical spine at the C6/7 level (60% of vertebral body anterior-posterior length), laceration of the dura with a small epidural hematoma at this level and an incomplete spinal cord lesion (anterior cord syndrome). The sunvisor contact deflected the head rearward, as the neck was being loaded in a extension compression mode and the head and face next impacted the windshield leaving tissue transfers in the windshield and causing corneal abrasions to the right eye and lacerations of the right eyelid. The head impacts resulted in a cerebral concussion Grade III with loss of consciousness for a period between 15 minutes and 1 hour.[10] Subsequent torso impact with the right edge of the protruding instrument panel (which extended across the drivers side and about 8cm into the passenger side of the vehicle). This contact caused fractures of the left 3rd and 4th ribs marked by transfer of fur from the victim's coat. Secondary impacts with the dashboard panel resulted in fracture of the right 1st rib. Associated chest injuries included bilateral pulmonary contusions, pneumothorax, and myocardial contusions.

Analytical Reconstruction, Case 2

The predicted kinematics of the occupant impact are shown in Figures 2.B. thru 2.G. Figure 2.B. shows the initial position of the occupant. The vehicle interior showed evidence of chest contact at a distance 8cm to the right of centerline. Therefore, it was assumed that the occupant was seated with her left shoulder close to the centerline and with her legs angled to the right. Figure 2.C. shows the occupant position at 100 ms. At this point in time, the head is undergoing a glancing contact with the sunvisor/header, causing a neck loading of 5ms duration.

Figure 2.D. shows the occupant position at 110 ms. This point is shortly after the initial head contact with the windshield. The maximum head acceleration values of 12600 rad/sec^2 angular and 110G linear were produced at approximately this time. The HIC of approximately 240 occurred between 107 and 121 ms. Figure 2.E., 2.F. and 2.G. show the continued rotation of the head at 120, 130 and 160 ms, respectively. The calculated neck extension moment exceeded 108 Nm during the period between 135 and 155 ms. The head impact and neck loading data for this case are summarized in Tables I and II.

Summary of Accident Case 3 Head Injury

The accident victim was an unbelted driver of a 1982 compact sedan who was involved in a frontal impact with a pole. (Case number HNH-28-207; Simulation AB01). The occupant was a 52 year old male, approximately 6" feet tall and weighing 170 lbs.

The vehicle sustained a maximum crush of 18 inches. The velocity change was estimated to be approximately 15 mph based upon a computer reconstruction using the crash program. The direction of primary force was between - 5 and - 15 degrees. A schematic drawing of the interior damage is shown in Figure 3.A. The evidence of interior body contacts include a star pattern on the windshield caused by head contact; a cracked lower dashboard plastic panel from left knee contact, and a dented lower dashboard metal panel from right knee contact. The steering column stroked approximately 1cm. There was no damage to the steering wheel. It may be noted from damage areas shown in Figure 3.A. that the victim moved forward and to his left.

Case 3 Occupant Injuries

In the motor vehicle accident report by the police it is noted that the driver of the crash vehicle was "highly intoxicated", however a blood alcohol level was not obtained. He sustained a significant head injury caused by impact with the windshield resulting in a cerebral concussion Grade III with loss of consciousness for a period between 15 minutes and 1 hour and with persisting retrograde and post traumatic amnesia. Lacerations on the left forehead and chin, most probably induced by the windshield were cleaned and sutured "per primam".

In addition, the victim's motion forward and to the left was also impeded by the steering wheel which caused significant abdominal injuries including a large bruise of the right abdomen, laceration of the liver, spleen, and hepato-duodenal ligament. There were also associated fractures of the 3rd, 4th and 5th ribs on the right produced by the torso impact with the steering wheel. Although both knees contacted and bent or broke components of the lower dashboard, there were no significant knee injuries.

Analytical Reconstruction, Case 3

The predicted kinematics of the occupant are shown in Figure 3.B. thru 3.D. Figure 3.B. shows the initial position of the occupant. It is assumed that the occupant was normally seated. Figure 3.C. shows the occupant position at 130 ms. At this point in time the lower rim of the steering wheel is in contact with the abdomen and the knees are in contact with the lower dash. Figure 3.D. shows the occupant position at 150 ms. The initial head contact with the windshield occurred at approximately 147 ms, and the maximum linear and angular accelerations of 86g and 7500 rad/sec^2 respectively, occurred at approximately this time. The HIC of 170 occurred between 144 and 148 ms. The head impact data for this case are summarized in Table I.

DISCUSSION

It is undoubtedly true that attempts to correlate probable occupant kinematics with real occupant injuries in real world accidents is a difficult task. There are, however, three advantages of our approach. First, by beginning the accident investigation at a time which is closer to the time of arrival of the victim at the hospital we tend to obtain more reliable crash data. Second, by having one accident investigation team work closely with only one hospital trauma service and by organizing intergrated data reviews at regular intervals by both engineering and medical teams, we improve the quality of the patient injury data by mutual education on what is most important to look for. In this way we believe that our developing data base could provide a valuable source for physical and analytic reconstruction. Third, by using analytical reconstruction, we are able to gain insight into the conditions which caused the injuries.

The analytical simulations presented in this paper are samples of applications of the CVS-3D model. The precision of the simulations is dependent upon a number of factors including the knowledge of the initial occupant position, the crash acceleration and its direction, the human occupant properties, and of the properties of the interior vehicle panels and their location and relative displacement.

The initial occupant position can be inferred by matching the damage areas predicted for various seating positions. The magnitude and direction of the crash pulse is determined from the crash computer program (4).

The acceleration time history is based upon crash test data for similar vehicles. The human occupant properties used were based upon dummy models discussed in reference 3 and 7. The location of the vehicle interior panels was based upon measurements of similar vehicles which were undamaged. The properties of the vehicle interior were based upon tests conducted by the Transportation Systems Center (6). For Case 2, Simulation CC00, the interior of an identical vehicle had been tested. Therefore, excellent information was available for this simulation. We intend to replicate our simulations for validation against similar physical tests.

For Cases 1 and 3, test data on the vehicle interior was not available. Therefore, the vehicles were assumed to have properties similar to other contemporary vehicles by the same manufacturer. As additional test data becomes available, the simulations may be further improved.

Certain comments on our preliminary results are of interest. First of all, in two of the cases (Nos 2 & 3) the occupants sustained a significant head injury with a Grade III cerebral concussion according to the classification suggested by one of us in a recent review of the biomechanics of head injuries (10). The calculated HIC values for Cases 2 and 3 were less than 250 while Case 1 with no head injury produced a HIC of +300. However, the two cases with head injury sustained higher angular acceleration levels than the case without head injury. This finding is in agreement with experimental data on the significance of angular acceleration in the mechanism of cerebral concussion and related diffuse injuries to the brain (10).

Case 2 sustained a peak angular acceleration of approximately 13,000 rad/sec,^{2} about twice that of Case 1. The angular head acceleration for Case 3 was only about 15% higher than for Case 1. However, it is interesting to observe that Case 3 was "highly intoxicated", which may contribute to injury susceptibility (11). Although classified as an AIS-2 injury by the AIS-80 (9) rubrics, current understanding of the outcome of such "minor to moderate" head injuries as found in our Case Nos. 2 and 3 clearly suggest that we should consider them more serious in terms of their resultant disability (12). It should be noted that both of these concussive brain injuries occurred at relatively low values of dv = 18 and 15 mph.

In order to gain additional insight into the neck injuries which occurred in Cases 1 and 2, the loads and moments at the head to neck joint were calculated using the methods reported in Reference 8. The results, summarized in Table 11, show that Case 1 sustained forces of 1500 N shear and 4200 N compression for a period of 3 ms while undergoing a flexion moment of 113 Nm. A flexion moment in excess of 68 Nm was sustained for 20 ms. Case 2, on the other hand, involved an extention moment which peaked for 3 ms at 124 Nm. The extension moment exceeded 108 Nm for 20 ms. The peak compression and shear loads were approximately 1100 N.

Although these forces and moments were calculated at vertebra C1 rather than C5/C7 where the injuries occurred, they provide estimates which can be compared with experimental measurements made using the Hybrid III dummy neck instrumentation. These simulations are the first attempt to use the 3D model for calculating neck loads which produced injuries. Additional simulations are planned to further investigate the relationship between 3D simulation and tests using the Hybrid III dummy.

The analytical results presented in this paper are samples of several applications of the CVS model to compute the conditions which were associated with head and neck injuries. The simulated results are generally in the range expected. Parallel work is underway to further improve the simulations. This work includes: Static and dynamic testing of vehicle interior components, improvement of occupant model to include additional human characteristics, and validation of the force and moment calculations at the head/neck junction. A more detailed presentation of our data including its experimental basis will be reported in the near future.

The 3D occupant model provides excellent insights into the kinematics of the occupant during the crashes simulated. The ability to calculate neck forces and moments, as shown in Table II, significantly aids in interpreting the neck injuries sustained by the accident victims. Continued usage and experience with the model will improve the confidence and precision of the simulations.

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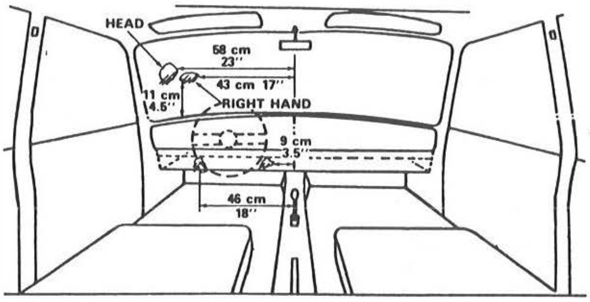
TABLE I HEAD IMPACT DATA

CASE NO.	DELTA V MPH	OCCUPANT DATA	HIC	COMPUTED HEAD ACCELERATIONS LINEAR G	ANGULAR RAD/SEC**2	HEAD/NECK INJURIES
1 LB01	26	HEIGHT 5'7" WT. 160 LB MALE BAC=0	330	100	6300	SPINAL CORD INJURY (QUADRIPLEGIA) WITHOUT SPINAL CANAL DAMAGE. NO SIGNIFICANT HEAD INJURY.
2 CC00	18	HEIGHT 5'6" WT. 135 LB FEMALE BAC=0.23	240	40 110	4500 12600	SPINAL CORD INJURY (INCOMPLETE) WITH C6/7 SUBLUXATION. HEAD-CEREBRAL CONCUSSION GRADE III
3 AB01	15	HEIGHT 6' WT. 170 LB. MALE BAC NOT DONE HIGHLY INTOXICATED	170	86	7500	NO NECK INJURY HEAD-CEREBRAL CONCUSSION GRADE III

TABLE II NECK LOADING

CASE	FORCES-3MS. SHEAR N	AXIAL N	TIME MS	BENDING MOMENT MAX NM	SUSTAINED NM	DURATION MS	TIME MS
1 LB01	1500	4200	110	-113	-68	20	96-116
2 CC00	3400	1900	112	68	57	05	104-109
	1100	1100	157	124	108	20	135-155

INTERNAL VEHICLE DATA



LIST OF CONTACTS	RESULTS OF CONTACT
HEAD TO WINDSHIELD	OILY TRANSFER
RIGHT HAND TO WINDSHIELD	OILY TRANSFER
CHIN TO STEERING WHEEL	NO DAMAGE
CHEST TO STEERING HUB	NO DAMAGE: 1 cm COLUMN STROKE
ABDOMEN TO STEERING RIM	NO DAMAGE
KNEES TO DASHBOARD	DENTS AS SHOWN

CASE 153-05-0784
SIMULATION LB01

Figure 1A.

TIME = 0 MSEC

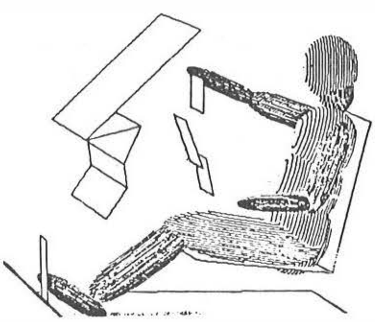


Figure 1B.

TIME = 60 MSEC

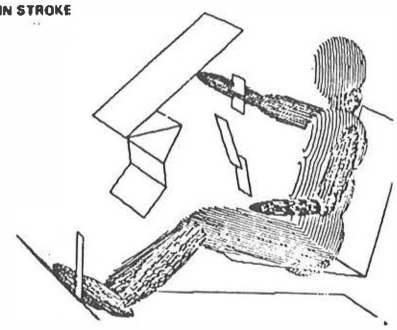


Figure 1C.

TIME = 80 MSEC

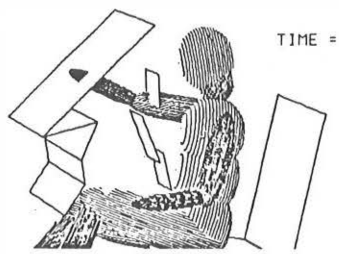


Figure 1D.

TIME = 100 MSEC

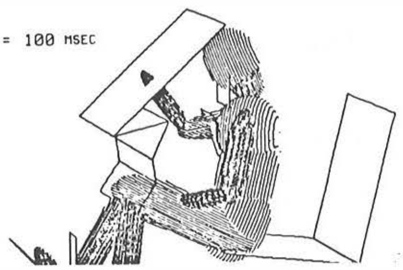


Figure 1E.

TIME = 110 MSEC

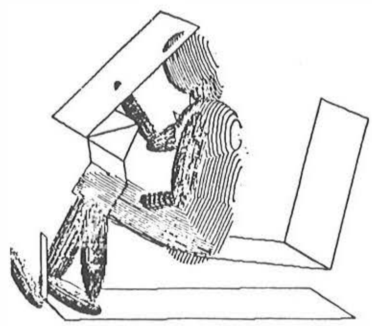


Figure 1F.

TIME = 120 MSEC

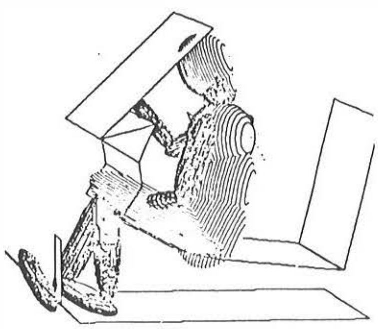
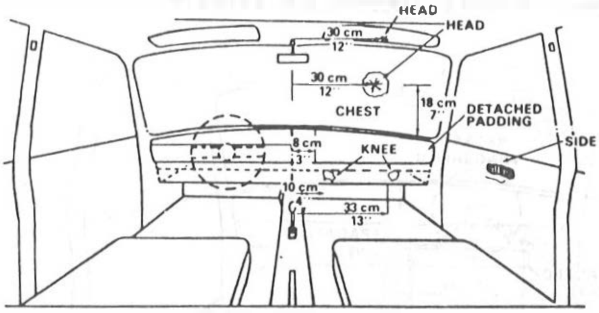


Figure 1G.

INTERNAL VEHICLE DATA



LIST OF CONTACTS	RESULTS OF CONTACT
HEAD TO HEADER	TISSUE TRANSFER
HEAD TO WINDSHIELD	TISSUE TRANSFER; CRACKED GLASS
CHEST TO DASHBOARD	DETACHED DASHBOARD PADDING
KNEES TO DASHBOARD	DENTS AND SCUFFS AS SHOWN
RIGHT SIDE TO DOOR	CLOTHING MATERIAL TRANSFER

CASE 141-011784
SIMULATION CCTD

Figure 2A.

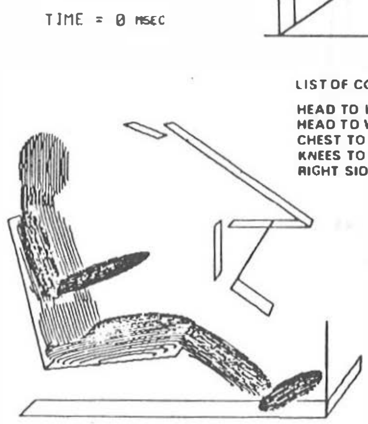
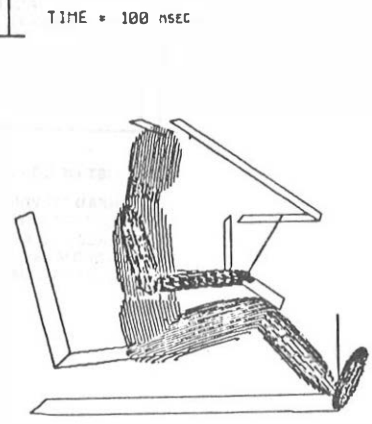


Figure 2B.



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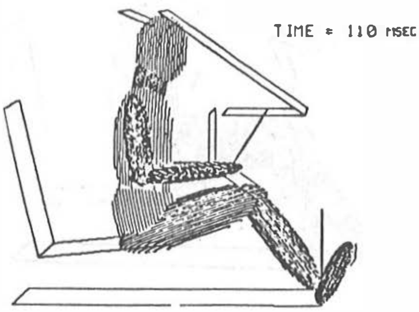

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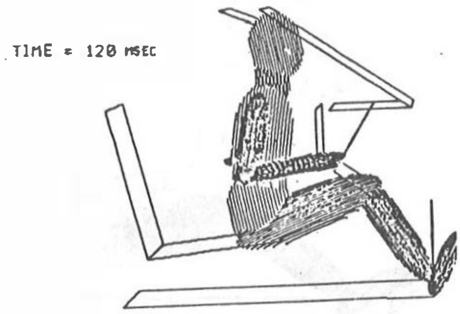

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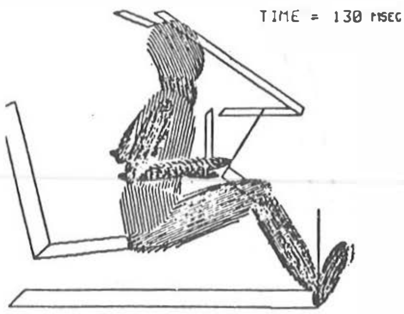

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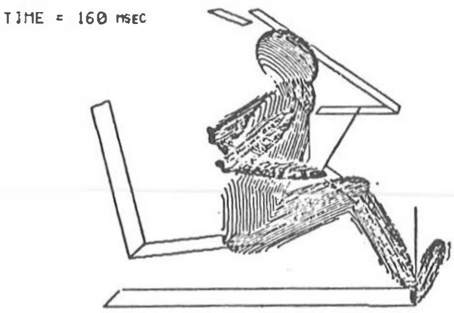
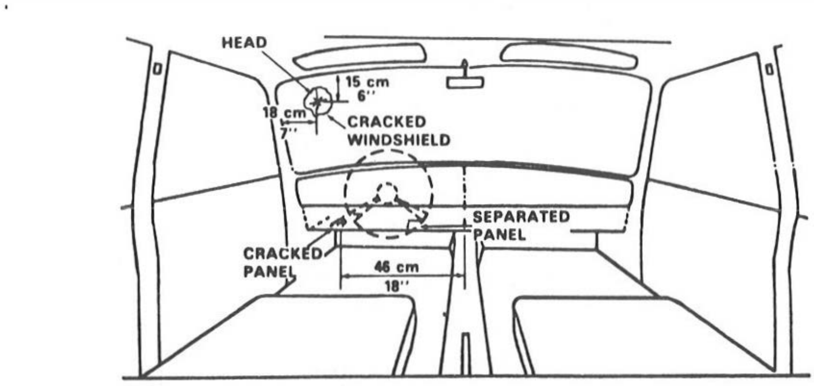


Figure 2G.

INTERNAL VEHICLE DATA



LIST OF CONTACTS	RESULTS OF CONTACT
HEAD TO WINDSHIELD	STAR CRACK IN WINDSHIELD
CHIN TO STEERING RIM	NO DAMAGE
CHEST TO STEERING WHEEL	NO DAMAGE; 1 cm COLUMN STROKE
ABDOMEN TO STEERING RIM	NO DAMAGE
KNEES TO DASHBOARD	CRACKS AND DENTS AS SHOWN

CASE HNH-28-207
SIMULATION AB01

Figure 3A.

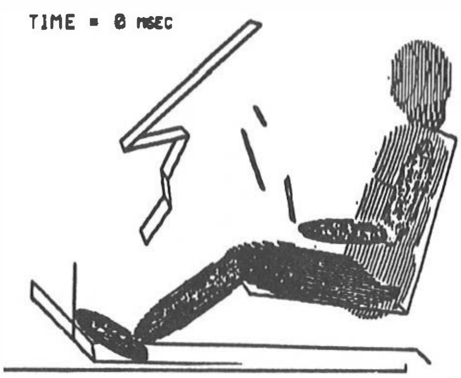


Figure 3B.

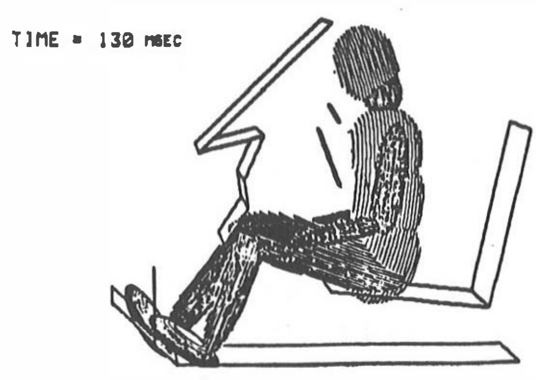


Figure 3C.

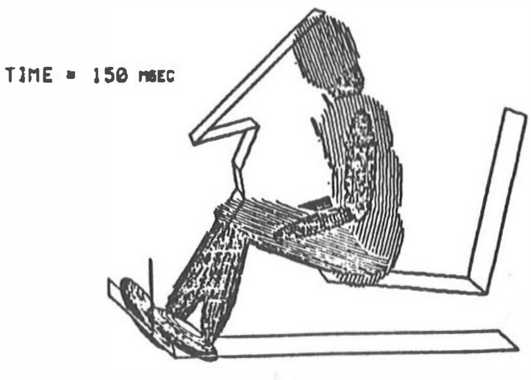


Figure 3D.