HUMAN HEAD IMPACT RESPONSE EXPERIMENTAL DATA AND ANALYTICAL SIMULATIONS

Sunder H. Advani, William R. Powell,
Jeffrey Huston and Steven J. Ojala

Department of Mechanical Engineering and Mechanics,
West Virginia University
Morgantown, West Virginia 26506 (U.S.A.)

ABSTRACT: The dynamic response of the human head is investigated using experimental data and analytical simulations. The head acceleration response is characterized from experiments on seated human cadavers subjected to frontal, occipital, and side head impacts. Acceleration time histories at the head vertex and at the front/occiput/side of the head are presented for measured force time histories and impact velocities. Response results from a detailed multi-degree of freedom model, incorporating inertial and constitutive properties of the head-neck system, are also presented. Finally, head injury criteria are discussed on the basis of experiments and model analysis.

INTRODUCTION: Several experimental and analytical efforts have been recently directed toward characterization of the mechanical response of the human head [1, 2]. The experimental studies have primarily entailed measurement and comparison of head motion responses of human volunteers, cadavers, animals, and test devices (dummies) to controlled impacts. The analytical investigations have concentrated on the dynamic response solution and validation of discrete parameter and continuum models. Injury mechanisms, thresholds, and criteria formulated from these studies provide a basis for support-restraint system and vehicle design.

Extensive sled data on the human head neck response to inertial accelerations, using human volunteers, has been presented by Ewing and Thomas [3]. The acceleration levels in this work range from 5-10G with typical angular accelerations of about 1000 rad/sec^2. Generalli et al [4] have reported on the injurious effects of rotational and translational components of head acceleration in squirrel monkeys. McElhaney et al [5] have presented force-time and corresponding head acceleration time profiles for human cadaver frontal and side head impacts. Current research at Wayne State University [6] and the Highway Safety Research Institute [7] is concerned with the measurement of three dimensional human cadaver head motion. Computational difficulties have been encountered using data from two triaxial linear accelerometers. These problems are being rectified by employing six or nine suitably positioned accelerometers. Additionally, accelerometers for separating skull vibrational effects from the head rigid body motion are necessary.

This paper presents human cadaver head acceleration-time responses to direct frontal, occipital, and temporal head impacts. Additionally, head-neck model simulations, results, and data from high speed films (1000 frames per sec) are presented.

EXPERIMENTAL METHODS AND PROCEDURES

The impact loading apparatus, shown in Figure 1, consisted of a modified barber's chair to position and retain the cadaver, a striker pendulum with interchangeable striker heads, and a pendulum support frame. The cadaver, when seated and secured in the chair, was positioned for either frontal or occipital or side head impact by rotating and adjusting the chair. Impact velocity measurements were made with a switch activated by a cam on the pendulum arm. Pezoelectric force transducers mounted behind the striker face plate were used to measure impact forces.

Two triaxial accelerometers (Entron) were mounted on the skull at the head vertex and either occipital or frontal or temporal positions depending on the location of the impact. On some tests, the triaxial accelerometers were supplemented with two single axis Kistler accelerometers on the skull. Figure 2 illustrates a cadaver, with vertex and temporal accelerometers, positioned for side head impact.

The impact series began with a relatively low velocity impact to verify the proper operation of the instrumentation and recording equipment. The impact velocities were subsequently increased until skull fracture was realized or considerable neck tissue tearing was detected. High speed motion coverage, using a Hycam camera, was made of several impacts.

EXPERIMENTAL RESULTS

The frontal, occipital, and side head impact results reveal considerable variability in dynamic responses. Factors influencing the measured responses include striker weight, initial cadaver head positioning, sites and inclinations of head accelerometers, cadaver properties (neck stiffness, head mass, etc.), skull vibrations, and location of impact. A peak impact force versus impact velocity representation of the head impacts is illustrated in Figure 3. A linear trend is evident for cadavers #4, #8 (side impacts), cadaver #3 (occipital impacts), and low force level frontal impacts. The scatter in the data for cadaver #9 can possibly be attributed to progressive scalp/neck tissue tearing and/or cumulative skull indentations. The impact force durations in these impacts typically range from 5 to 10 msec with rise limits of 2 to 3 sec.

The terminology for characterizing the head accelerometer plots is given in Table I.

Table I: Terminology for Head Acceleration Response

$+G_x$, $-G_x$	Forward, Backward head accelerations respectively along head anterior-posterior axis
G_y	Lateral (Side) head acceleration along head temporal axis
$+G_z$, $-G_z$	Headward, Tailward head accelerations respectively along head superior-inferior axis

Since the frontal, occipital, and temporal impacts produced head motion primarily in the (X, Z), (X, Z), and (Y, Z) planes respectively, the acceleration component for the corresponding third axis was recorded only for a few impacts. This third axis component, in all subfracture cases, indicated small inertial acceleration magnitudes with skull vibration components. The accelerometer direction cosines (d.c.^{s}) are identified in the response plots so that conversion from the head coordinate reference frame to the laboratory reference frame (used for the Hycam data) can be made.

Results of two subfracture frontal impacts with a 9.1 Kg (20 lb) striker head are shown in Figure 4. The force-time characteristics for all the head impacts exhibit these triangulated pulses. The acceleration time pulses generally follow the forcing function with superimposed skull vibration contributions. Impact force and striker, frontal, and vertex acceleration-time plots for four occipital head impacts are given in Figures 5 and 6. In Figure 6, the impact force and acceleration-time histories for a 0.038 m (1.5in) padded styrofoam impact are compared with results from a conventional impact at the same impact velocity of 2.74 m/s. The padded and unpadded peak forces are 1.43 KN and 6.58 KN respectively. Figure 7 illustrates impact force and tri-axial vertex acceleration-time profiles for a skull fracture producing side impact. As expected, significant skull motion is evident along the three head axes.

HEAD IMPACT MODEL RESPONSES

The three-dimensional dynamic head-neck model, Figure 8, consists of nine rigid bodies. It includes the head, seven cervical vertebrae, and the torso with options to incorporate two additional bodies, namely, the brain and the jaw. The rigid bodies are connected together by combinations of intervertebral discs, ligaments, and muscles. The six intervertebral discs below C-2 through T-1 are modeled by assuming the vervical vertebrae as rigid and the discs as viscoelastic with axial bending, and shear effects included. The neck ligaments are modeled with non-linear elastic springs and the muscles are modeled as viscoelastic Kelvin elements. The ligaments and muscles are assumed to act in the tension mode only. Figure 9 shows the atlanto-occipital, the atlanto-axial, and the axial-C3 joints. The first two joints are of particular interest since they have no intervertebral discs. The axial-C3 joint is illustrated as a typical joint for all other joints below it. Joint stopping forces and torques are applied to the rigid bodies when their range of motion limit is reached. Since there are six degrees of freedom at each joint, the model can simulate neck motion in flexion-extension, lateral flexion, rotation, and stretching. The model has the flexibility for specification of force or acceleration inputs to the head or torso, and it predicts linear and angular displacement, velocity, and acceleration of the head and seven cervical vertebrae. Dynamic forces in the discs, ligaments, and muscles are easily obtainable and rotation and translation of the brain can also be determined. The governing coupled equations of motion, written in the D'Alembert form of Lagrange's equation, are numerically solved by the Runga-Kutta integration routine. Figure 10 shows the dynamic head center of gravity displacement, velocity, and acceleration obtained from the model simulation and differentiation of data from high speed movies (1000 frames per sec) for two sequential frontal impacts with impact velocities of 2.91 and 2.83 m/s (9.1 Kg striker). The peak computed angular acceleration for these impacts is about 3000 rad/sec^2.

DISCUSSION AND CONCLUSIONS

The skull surface acceleration-time profiles illustrate that vibrational effects superimposed on the inertial motion greatly influence the local magnitudes and time characteristics. Since the fundamental skull-brain natural frequency is about 500 HZ and the impact force rise times (rigid impactor) are about 2 to 3 msec, the significance of skull oscillatory motions in the accelerator tracts is apparent. The magnitude of the vibrational accelerations relative to the inertial value suggests that closed head, for rigid impacts, can be induced by oscillatory accelerations at the contrecoup site. For padded impacts, the inertial response is dominant and higher impact levels are required to produce contrecoup injury.

The model simulation and high speed photographic data both suggest significant rotational effects. The region at the base of the ear acts as an instantaneous center for the contact phase and subsequently undergoes linear motion for frontal as well as occipital impacts. The Hycam data also reveals considerable scalp-skull motion particularly at the impact site. The maximum radial displacement of the scalp surface was obtained to be about 0.006 m at the impacted occipital site using a22.7Kg striker with an impact velocity of 4.87 m/s and peak force of 6.39 KN. This value appears to be reasonable since the scalp itself compresses about 0.0045 m for an estimated contact stress of 2.76 MPa and resulting compressive strain of 60 percent [8], [9].

The average peak force magnitudes for the skull fracture producing impacts are: Frontal - 6.17 KN Occipital - 12.50 KN; and Temporal - 5.78 KN. The force durations in these impacts range from 5 to 10 msec. The fractures in all cases are depressed stellate fractures. The fracture force values are compatible with published data [9].

REFERENCES

1. Ommaya, A. K., "Head Injury Mechanics," Department of Transportation Final Report, Contract No. DOT-HS-081-1-106 1A, October, 1973.

2. Goldsmith, V. W., "Biomechanics of Head Injury" in Biomechanics - Its Foundations and Objectives, ed. Fung, Perrone, Anliker, Prentice-Hall, Inc., Englewood Cliffs, N.J.:1972, pp. 585-634.

3. Ewing, C. L. and Thomas, D. J., "Human Head and Neck Response to Impact Acceleration," NAMRL Monograph 21, Naval Aerospace Medical Research Laboratory, Pensacola, Florida, 1972.

4. Genarelli, T., Ommaya, A. K., and Thibault, L. E., "Comparison of Translational and Rotational Head Motions in Experimental Cerebral Concussion," Proc. 15th Stapp Car Crash Conference, S.A.E., Inc., 1971, pp. 797-803.

5. McElhaney, J., Stalnaker, R., and Roberts, V., "Biomechanical Aspects of Head Injury" in Human Impact Response, Measurement and Simulation, Plennum Press, N. Y.: 1973, pp. 85-112.

6. Padaonkar, A., Krieger, K., and King, A. E., "Measurement of Angular Acceleration of a Rigid Body Using Linear Accelerometers," 1975 Winter Annual

ASME Meeting, ASME Paper No. 75-APMB-3.

7. Stalnaker, R., Personal Communications, 1975.

8. Advani, S. H., and Owings, R. P., Evaluation of Head Injury Criteria, SAE Paper 740083, 1974. Also in Press Transactions, SAE, Inc.

9. Melvin, J. and Evans, F., "A Strain Energy Approach to the Mechanics of Skull Fracture," Proc. 15th Stapp Car Crash Conference, SAE, Inc., 1971, pp. 66 -685.

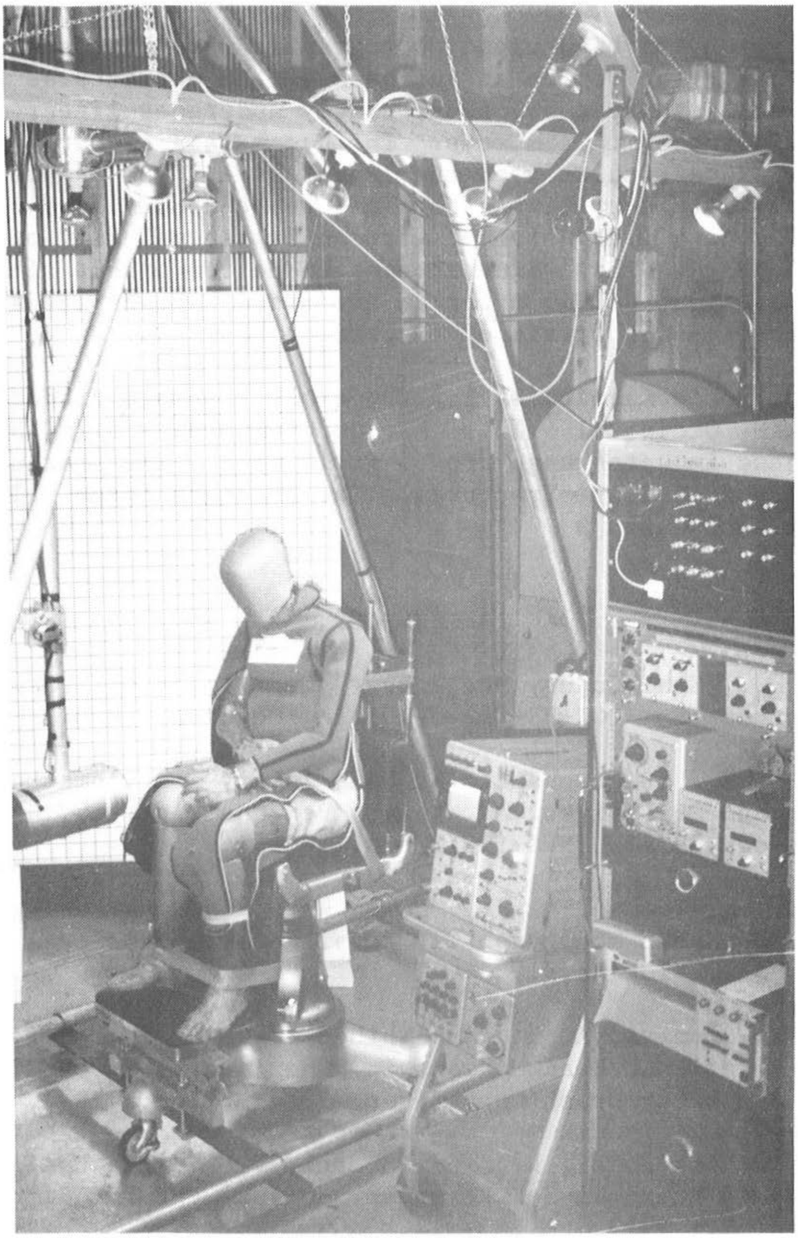

Figure 1. Impact Loading apparatus showing impact pendulum, support frame, recording equipment, and chair with experimental dummy.

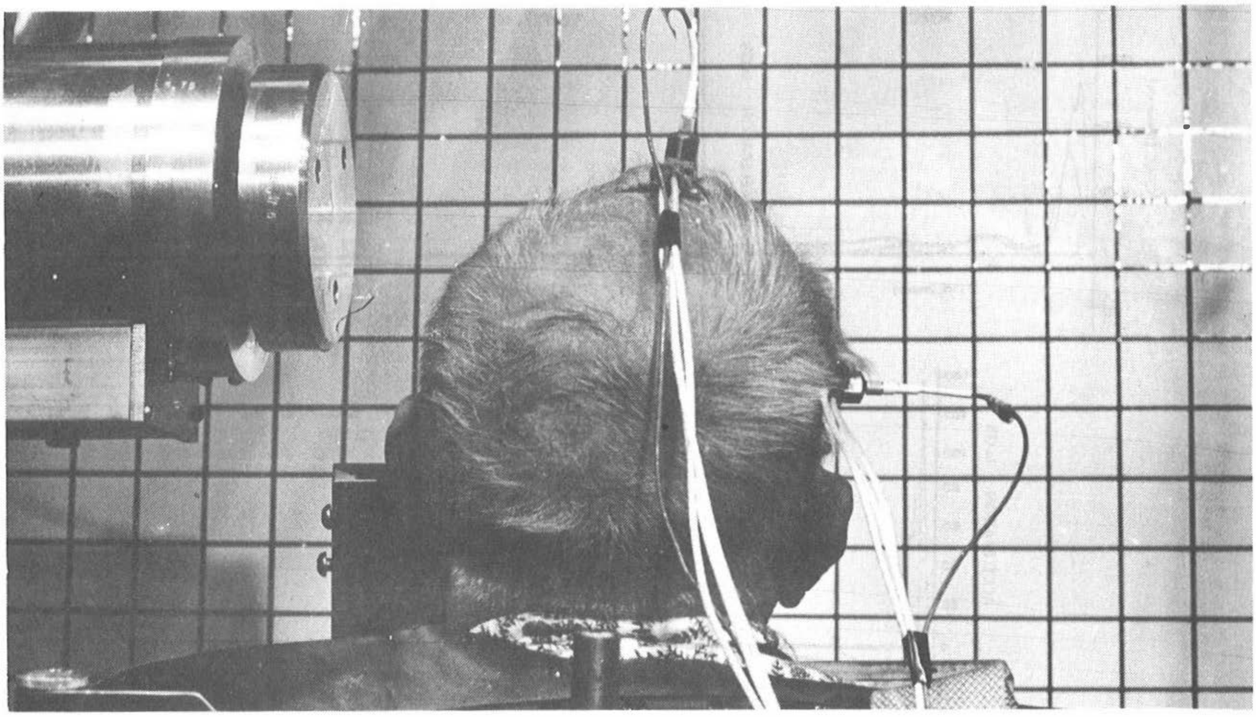

Figure 2. Cadaver head positioned for side head impact with both triaxial and single axis Kistler accelerometers mounted on skull vertex and temporal region.

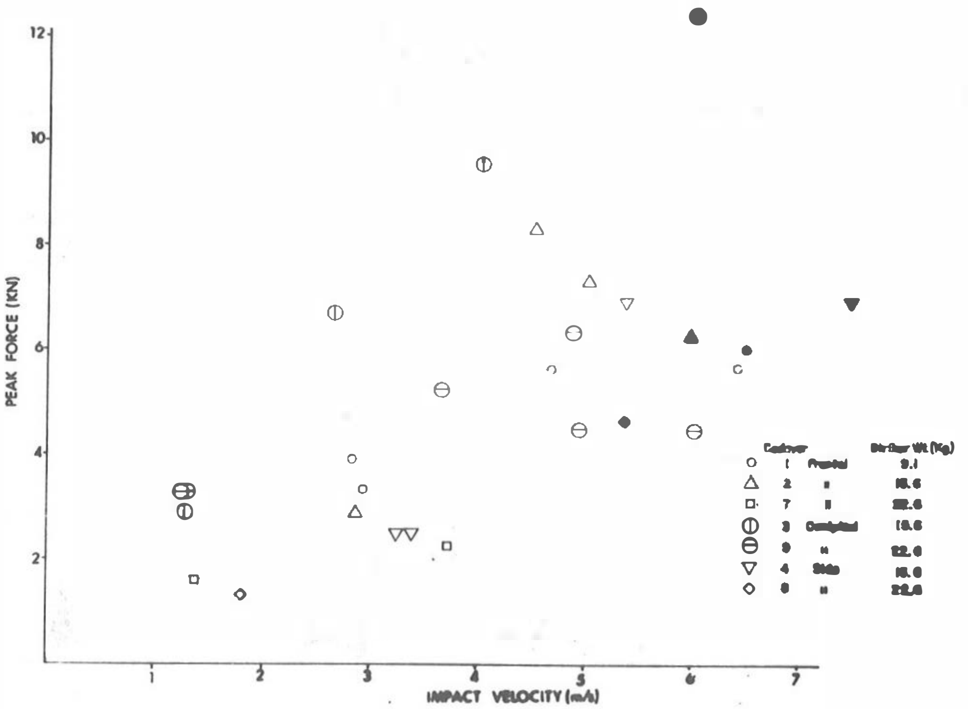

Figure 3. Peak force versus impact velocity for cadaver frontal, occipital, and side head impacts; filled in legends designate skull fracture producing impacts.

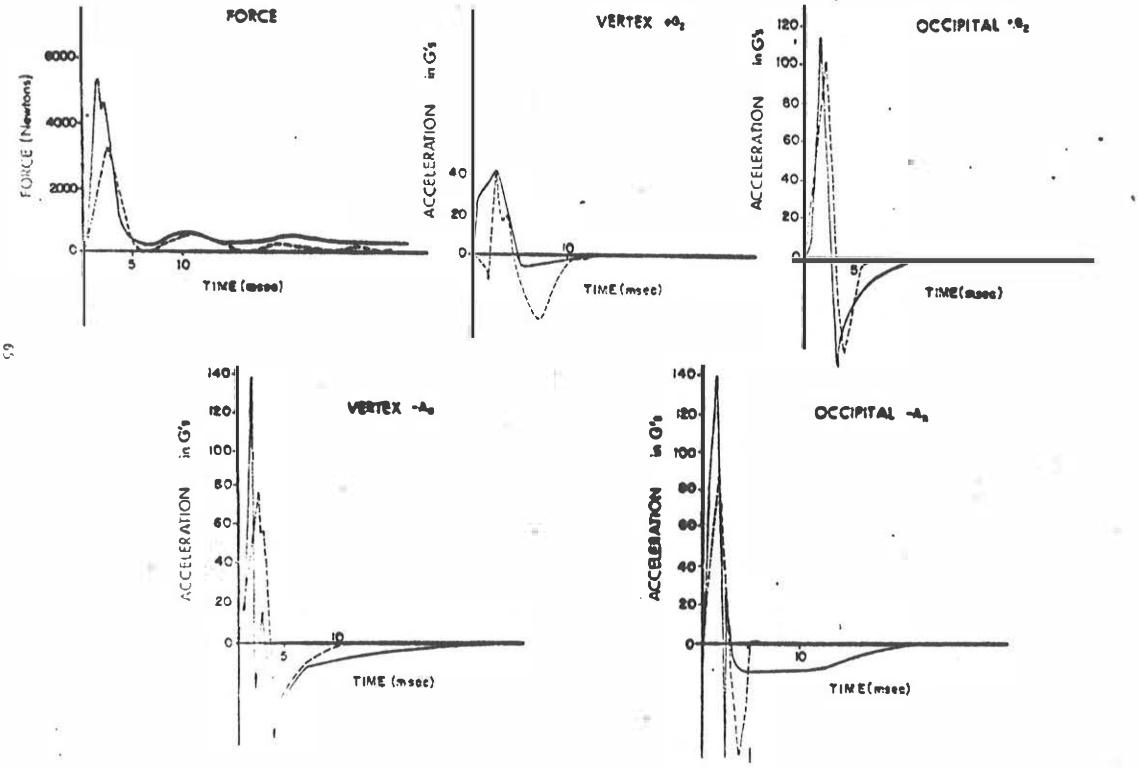

Figure 4. Force and acceleration time histories for two frontal head impacts. Impact velocities are 2.91 and 4.67 m/s. Approximate accelerometer d.c.'s are: vertex (0.96, 0, 0.26); occipital (0.94, 0, 0.34).

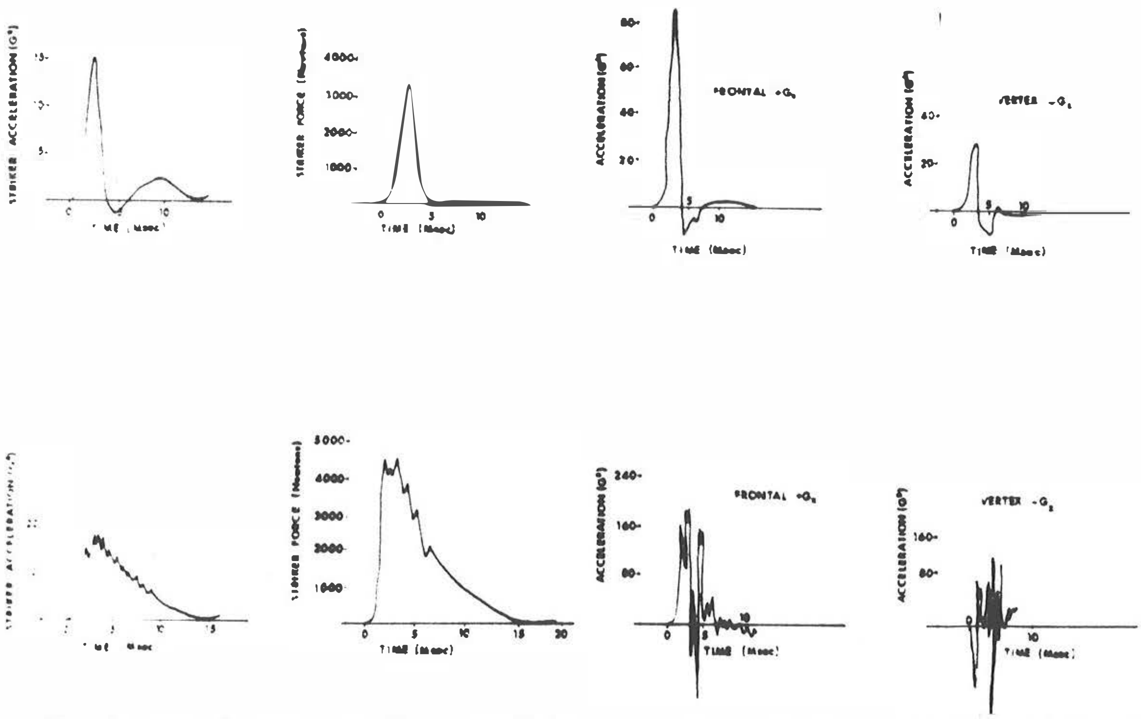

Figure 5. Impact force, striker acceleration and head acceleration plots for 1.26 m/s (above) and 4.92 m/s (below) velocity impacts with 22.7 Kg striker. Approximate accelerometer d.c.'s are: Frontal (0.86, 0, 0.05); vertex (0.50, 0, 0.86).

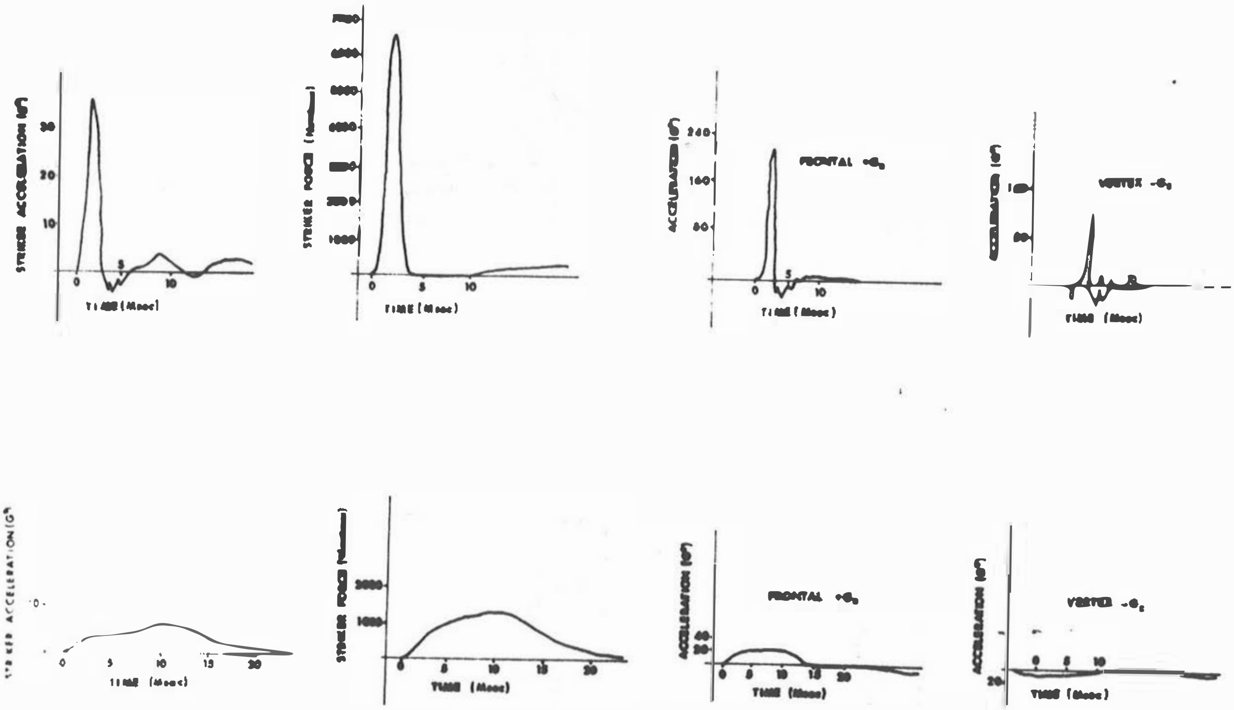

Figure 6. Impact force and acceleration histories for unpadded (above) and padded (below) impacts at same impact velocity of 2.74 m/s with 22.7 Kg striker. Approximate accelerometer d.c.'s are: Frontal (0.86, 0, 0.50); vertex (0.50, 0, 0.86).

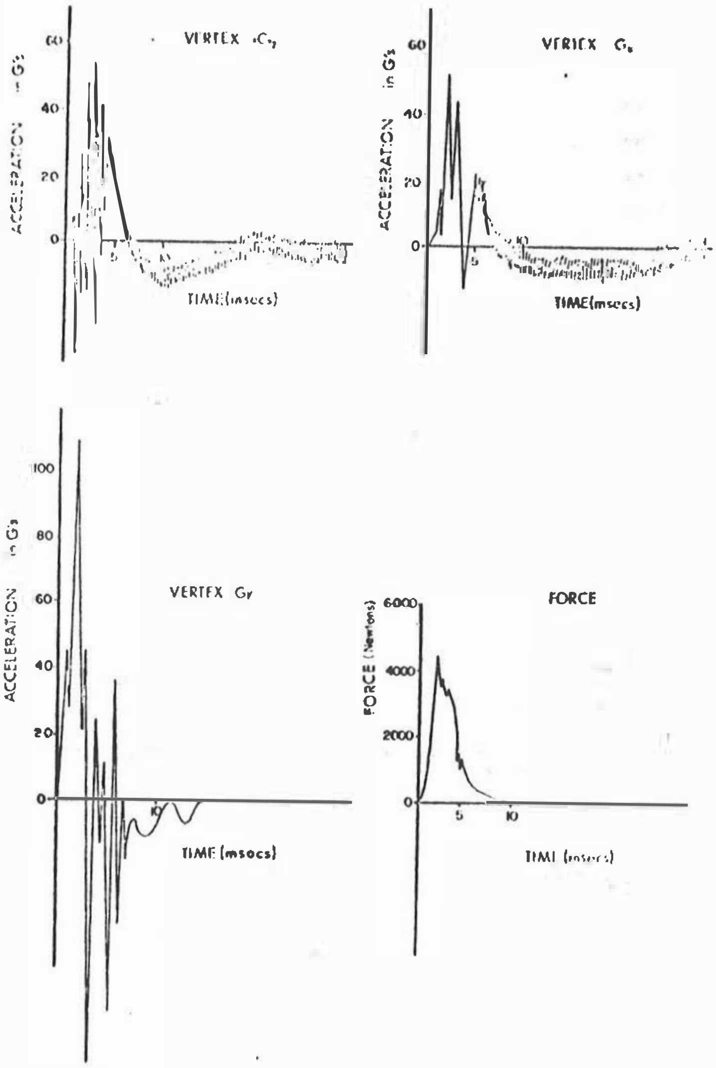

Figure 7. Impact force and acceleration time histories for skull fracture producing side impact (22.7 Kg striker) with impact velocity of 5.36 m/s.

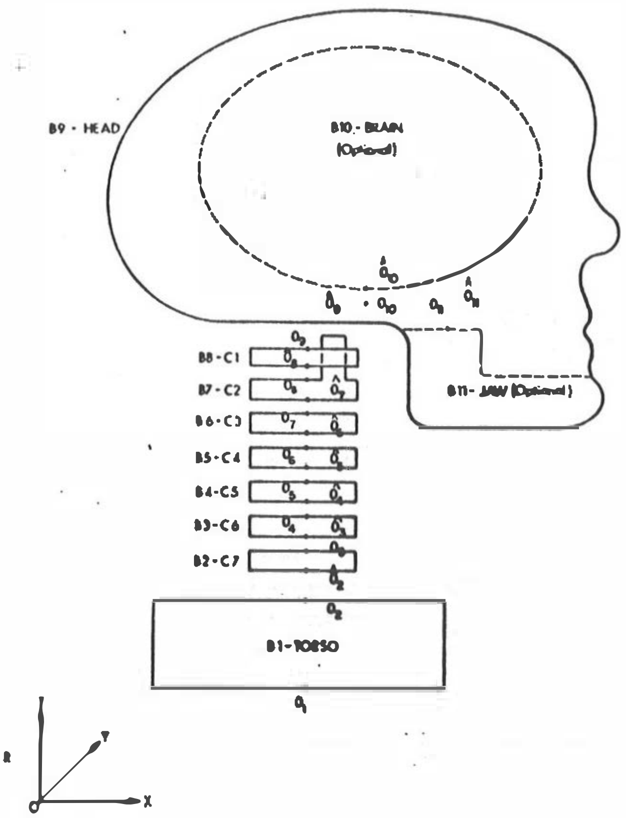

Figure 8. Three dimensional head-neck response model.

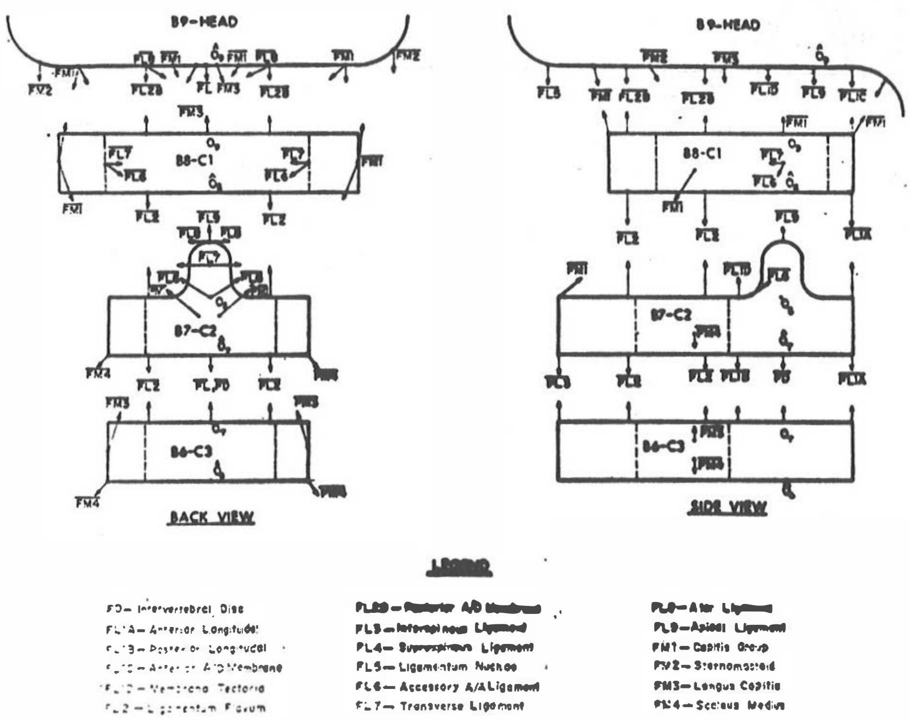

Figure 9. Connective tissue and joint details for head, C-1, C-2, and C-3.

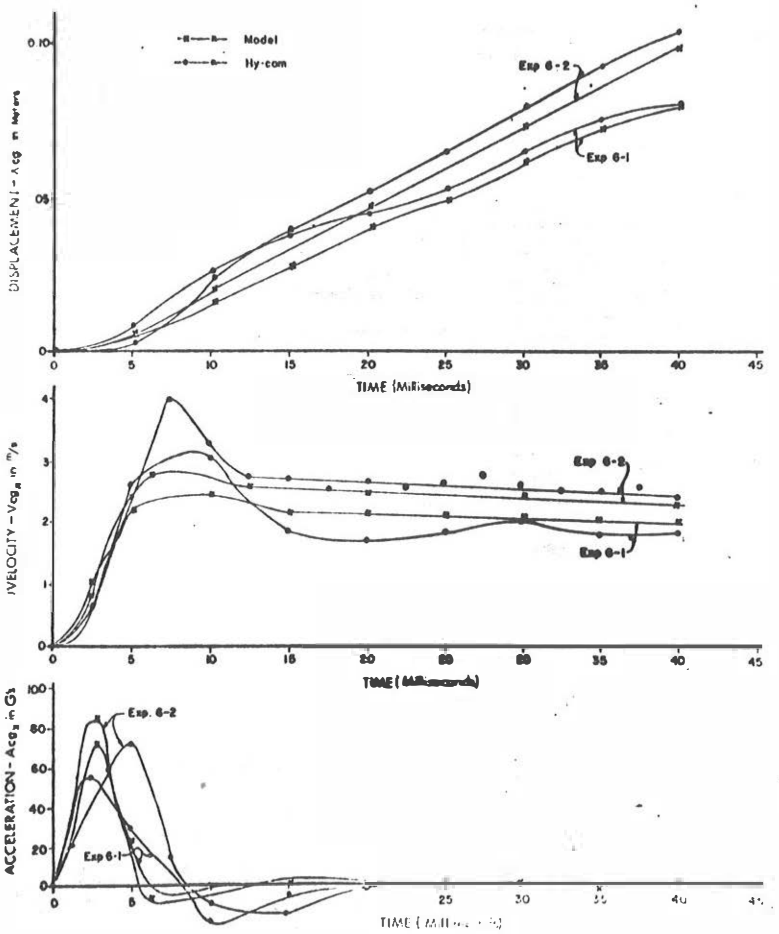

Figure 10. Displacement, velocity, and acceleration responses of head C. G. in forcing direction from high speed photographic data and model solution for two frontal impacts.