THE EFFECT OF SEATBACK STIFFNESS AND COLLISION SEVERITY ON THE DYNAMIC BEHAVIOUR OF THE HEAD DURING "WHIPLASH".

INTRODUCTION

Mathematical modelling has been described by McHenry (1) as a technique of physical research in which simplified idealisations are substituted for actual objects or systems. The final aim of such activity is directed not only towards an understanding of the behaviour of the modelled object or system but also towards the creation of a model with realistic, predictive capabilities.

In the field of biomechanics, the growing necessity to understand and predict the relationship between impact and injury has led to many such mathematical models, Garcia (2), Weaver (3). In many cases these models have been designed to reproduce the dynamic behaviour of the human body in the automobile accident situation. From the acceleration response to impact of such models the force patterns acting on body structures are inferred, or alternatively the acceleration levels are compared with previously established tolerance levels and hence the type of injury or the mechanism of injury may hopefully be revealed.

Recent advances in the biomechanics of impact injury, Hirsch et al (4) have indicated a need to extend current occupant dynamics models, in which forces acting <u>on</u> the body are predicted, to those in which a more direct investigation of the forces acting <u>within</u> the body can be obtained. An example of this trend has been an investigation of the forces and bending moments along the vertebral column following a vertical impulse to the body, Orne and Liu (5).

Accordingly this paper reports on how, by using Orne and Liu's method as a basis, a successful model was developed with a view to examining the dynamics of the head and cervical spine during rear-end impact to the restrained, seated, automobile driver.

REQUIREMENTS OF A MATHEMATICAL MODEL FOR WHIPLASH

Both medical and engineering literature and many experimental studies have indicated several features which are important and should preferably be incorporated into a model for "whiplash". Clearly the anatomical areas of interest are the brain, the structural components of the cervical spine, i.e. the vertebrae, and surrounding ligaments. Experimental work in which small animals were subjected to simulated rear-end impacts has emphasised the interest in concussion and permanent injury to the brain in addition to ligamentous and muscular damage. There has been considerable discussion on the mechanics of brain damage and concussion but the experimental work of Ommaya et al (6) has indicated that the rotational movement of the head is one of the important factors in acceleration-deceleration induced concussion.

The experimental investigations by Severy et al (7) and Berton (8) involving full scale rear-end collisions and those employing acceleration sleds by Mertz and Patrick (9) provide a further source of relevant factors, namely: the rigidity of the seatback; the height of the seatback; the initial angle of the head relative to the torso (commonly referred to as head offset) and the severity of the impact.

THE MODEL

As seen in Figure 1, the model at its present stage of development consists of: the head, the cervical spine (neck) and the torso-seatback unit. The head is represented as a rigid body with its centre of mass at G and mass moment of inertia I_8. The atlanto-occipital junction is at C. The seatback-torso unit is also modelled as a rigid body with centre of mass at D and mass moment of inertia I_1. The torso and seatback are combined into one unit under the assumption that the seatback substantially supports the torso for the major part of the collision duration. Deformation of the seat structure is controlled by non-linear, rotational springs as suggested by Martinez and Garcia (10). For rearward rotation the spring characteristics allow for deformation of the metal frame and incorporate the rotational characteristics of the body about the hips. For further rotation the deformation of the restraint system is added. At the seat rotation point H, an hydraulic damping factor has been included to allow for inelastic deformation which may occur, for example, by tearing of the floor pan of the vehicle.

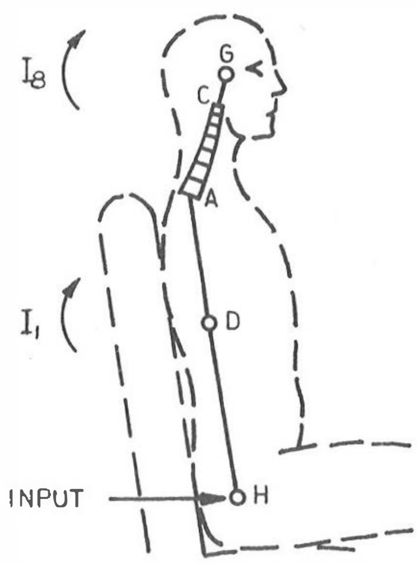

FIG. I MODEL OF THE HEAD-NECK-TORSO/SEATBACK

As mentioned previously, the cervical spine is modelled on the method of Orne and Liu and allows for the determination of the force and bending moment distribution in the neck. While the mass and mass moment of inertia of the vertebrae (as well as those of the head and torso) were determined from a consideration of data reported by Dempster (11) and Duggar (12) and also by Orne and Liu, the geometrical characteristics were obtained from a radiographic study of the neck of a 188 cm, 73 kg student male. The constitutive equations, and their associated material properties, governing the visco-elastic behaviour of the intervertebral discs were chosen to be the same as those used by Orne and Liu. These authors found that a wide range of combination of material parameters had little effect on the magnitude of the peak forces developed during deformation.

The impact acceleration profile was based on an approximation to vehicle response to full scale rear-end collisions, as observed by Severy et al. Accordingly a half sine function was used in the form:

$$a(t) = A_m \sin \omega t \qquad 0 < t \leq t_f$$

$$a(t) = 0 \qquad t > t_f$$

where A_m represents the peak acceleration reached by the impacted vehicle and t_f the pulse duration. The severity of the impact was controlled by suitable adjustment of A_m and t_f over a range of values as seen in Table 1.

Table 1

Range of Input Acceleration Parameters

Code No.	Amplitude A_m (g)	Duration t_f (m.sec)	$\frac{da(t)}{dt}$ (g/sec)
S	5	200	78.5
T	20	200	314.0
U	30	200	471.0
V	12	120	314.0
W	15	100	471.0
X	20	120	524.0

Seat stiffness and damping characteristics were not easy to obtain and reference was made in this regard to the previous work of Garcia (2) and Severy et al (7). From results reported by the latter it was possible to determine with reasonable accuracy the torsional rigidity of a rigidly constructed seat unit. For the range of impacts envisaged it was felt that elastic seat behaviour would dominate over inelastic behaviour and consequently the seat damping characteristic was assumed to be zero. The range of elastic stiffness parameters used is shown in Table 2. Note that ϕ represents the angular position of the seatback to the vertical and takes on negative values for rearward rotation.

Table 2

Range of Seat Stiffness Parameter (Kg.cm/rad.)

Code No.	$\phi < -17^\circ$	$-17^\circ \le \phi \le 0$	$0 < \phi \le 3^\circ$	$\phi > 3^\circ$
A	27,700	12,450	6,920	4,150
B	55,300	24,900	13,830	8,300
C	83,000	37,300	12,450	12,450
D	110,700	49,800	27,700	16,600
E	271,000	50,700	12,450	12,450
F	50,700	271,000	12,450	12,450
G	1,152,000	1,152,000	1,152,000	1,152,000

It will be noted that the model does not allow for adjustment of the seatback height and that for this series of calculations the height was taken to be equal to the shoulder height. However, it is intended that the model will be subsequently modified to include a head restraint device and as a consequence incorporate adjustment of seatback height.

The method of solution of the governing differential equations of the model has been previously discussed, McKenzie and Williams (13). Both the Predictor-Corrector and the Runge-Kutta methods gave comparable results, however, it was decided to use the former method for further investigations due to the reduction it afforded in computational time.

RESULTS

In terms of overall form and the relative appearance of peaks, the results of the model appear to agree reasonably well with the observed experimental results of Severy et al (7). More specifically, however, an examination of the elapsed times between the onset of a 200 m.sec. impacting acceleration pulse to the appearance of first, the shoulder peak accelerations and second, the head peak acceleration, Figures 2 and 3, reveal a considerable difference to those experimentally obtained by Severy et al. Their results for human volunteers show elapsed times of 230 - 250 m.sec. for the head and 200 - 240 m.sec. for the shoulders. When comparing these figures with the present model, 150 - 200 m.sec. for the head and 120 - 140 m.sec. for the shoulders, one is led to conjecture whether or not the accelerometer data of Severy et al truly represents the actual dynamic behaviour, whether this present model is properly formulated, or indeed, whether some degree of neuro-muscular feedback could be responsible for the discrepancy.

Effect of Seatback Stiffness

From Figures 2, 3 and 4 it can be seen that increasing seat

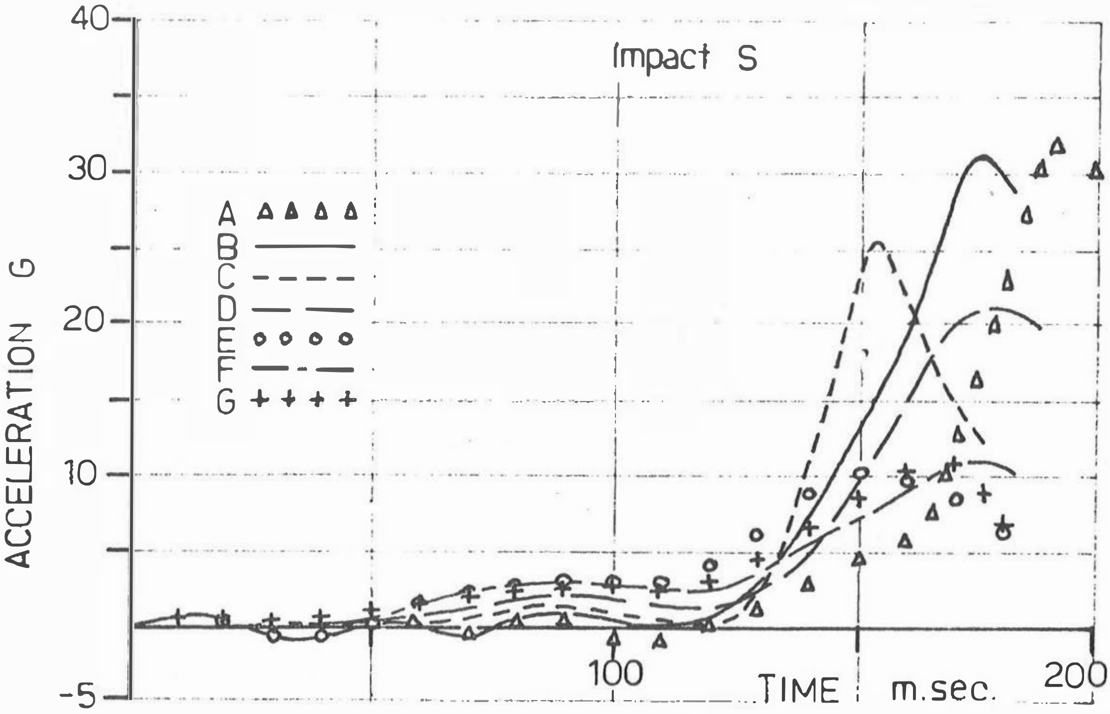

FIG. 2 HORIZONTAL HEAD ACCELERATION

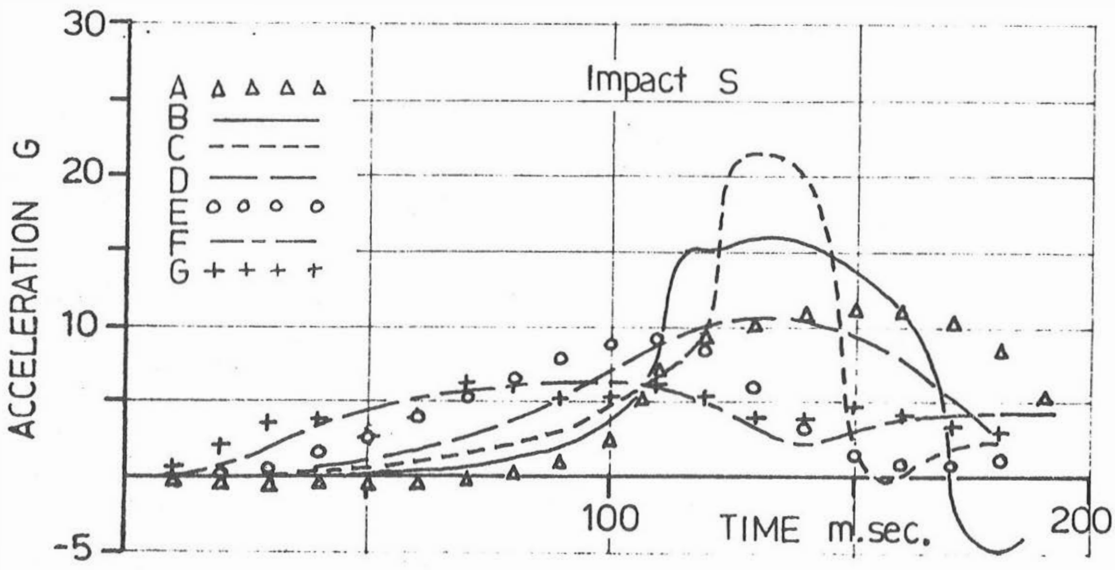

FIG. 3 HORIZONTAL SHOULDER ACCELERATION

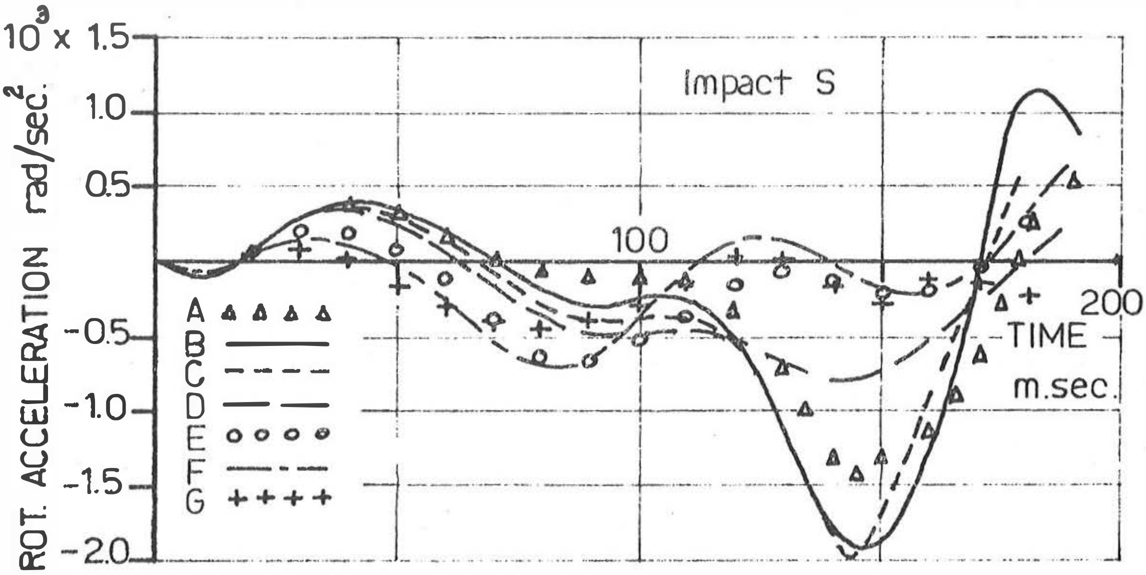

FIG. 4 ACCELERATION OF HEAD REL. TO TORSO

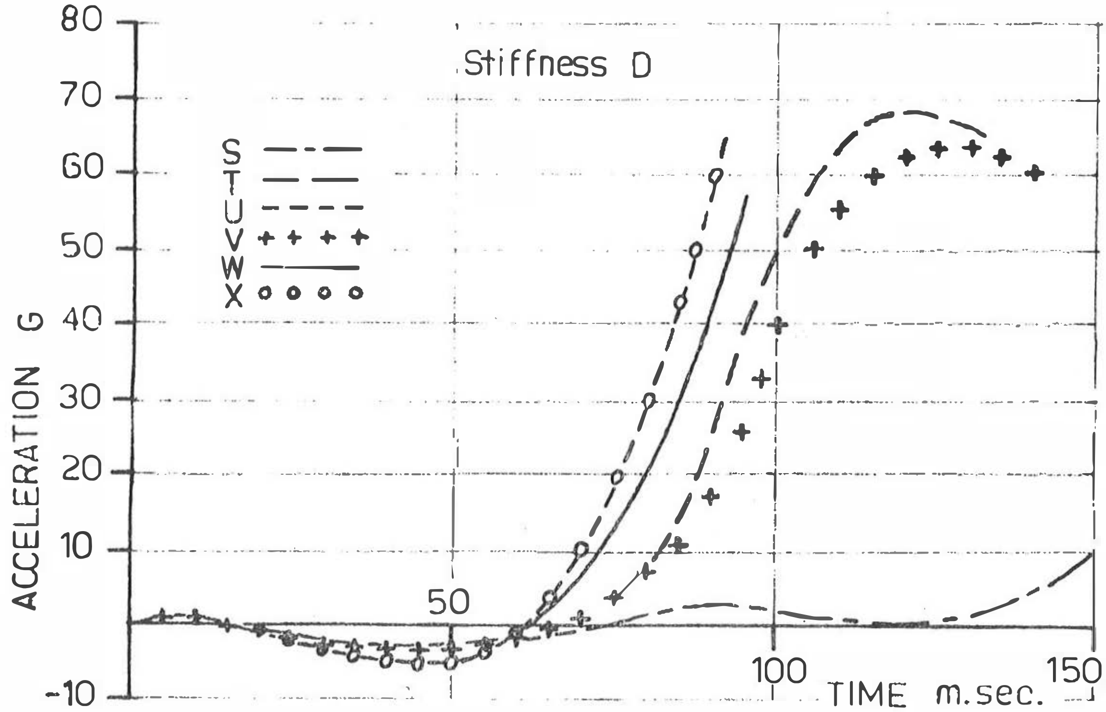

FIG. 5 HORIZONTAL HEAD ACCELERATION

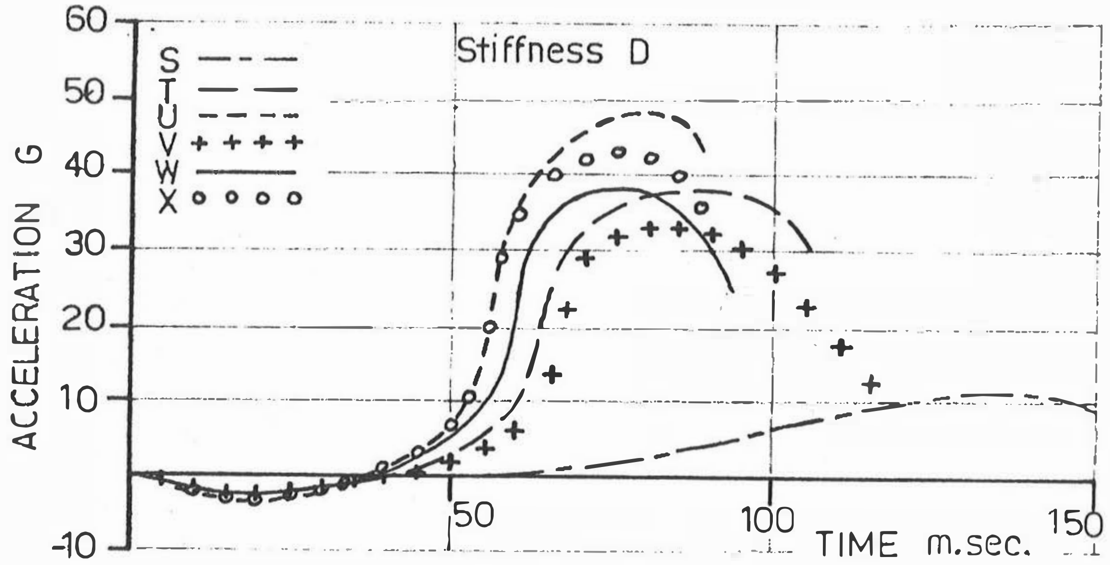

FIG. 6 HORIZONTAL SHOULDER ACCELERATION

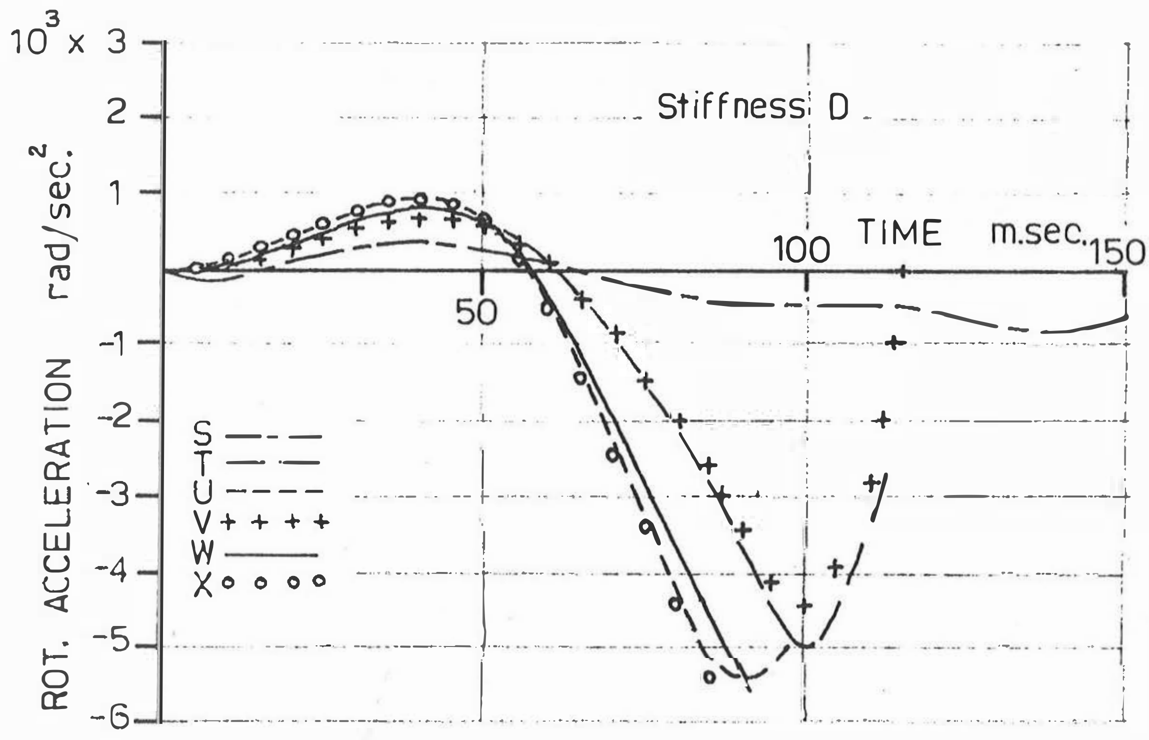

FIG. 7 ACCELERATION OF HEAD REL. TO TORSO

stiffness generally results in a decreasing of head horizontal acceleration. For a moderate increase in stiffness the decrease is apparent as shown by curves B, C and D, while for very stiff seatbacks, the head acceleration is considerably lower as shown by curves E, F and G, but there is no great effect in increasing rigidity beyond that value represented by curve E. An increase in shoulder acceleration occurs for an increase in seat stiffness from a relatively low value, Figure 3, but then decreases for a further increase in stiffness. Stiffnesses B and C appear to give the shoulders a particularly larger "jerk" than the other values. Maximum head rotational acceleration, Figure 4, varies in a similar fashion to maximum shoulder acceleration. With increasing seatback stiffness it first increases in magnitude and then decreases to a minimum value for seatback stiffness.

Effect of Collision Severity

In the investigation of collision severity the magnitude and duration of the input pulse was varied according to Table 1. It will be noted that in Figures 5, 6 and 7, curves S, T and V, U and W, and X correspond to increasing severity of collision. Using a seatback stiffness of D for comparative purposes it can be seen that for the higher severity inputs the shoulder acceleration peak occurs relatively close to the vehicle acceleration peak. In all cases it is followed by the peak head acceleration. Appart from curves X, U and W which terminated before reaching their peak values, it appears that the peak head horizontal acceleration occurs earlier with increasing severity. Except for the relatively mild collision there does not seem to be much difference between the time rate of change of head acceleration for a relatively wide range of more severe impacts. The corresponding shoulder accelerations are shown in Figure 6 showing a trend for increased maximum values occurring progressively earlier for increasingly severe impacts. The variation of rotational head acceleration is seen in Figure 7. From this it can be observed that there is an initial flexional rotational acceleration, the value of which increases with impact severity. A similar trend applies for the, much larger, extensional rotational acceleration. It is of interest to note that for impacts of increased severity the magnitude of rotational acceleration greatly exceeds the value of 1800 rad/sec^2 computed by Ommaya and Hirsch (14) which, theoretically, is required to cause human cerebral concussion in 50% of cases.

CONCLUSION

By comparison with previous experimental data it is apparent that the model proposed reproduces, reasonably faithfully, the planar motion of the head and neck during rear-end impact. An extension of the model to three-dimensional behaviour appears as the next step, however, nothwithstanding this current restriction, the information it yields is useful, both to a study of motion and forces in the cervical spine and to the development of more realistic necks for anthropometric dummies, Melvin et al (15).

The results indicate that as well as being related to impact severity, the magnitude of head and shoulder accelerations is clearly related to seatback stiffness with the possibility of a critical value of stiffness causing excessive loading to the head and spine. From an injury prevention point of view it would appear desirable to avoid low stiffness seatback construction.

Although not directly outlined in this paper, it was found that both the shear forces and bending moments were a maximum at the C6 - C7 junction. It was concluded therefore, that for increasingly severe impacts, the likely damage occurring during hyperextension of the neck would be tensile tearing of the anterior ligamentous structure for low stiffness seatbacks changing to the probability of compressive fraoture of the posterior regions of the vertebrae (lips and/or articular facets) for high stiffness seatbacks.

Finally, the relationship between impact severity and head rotational acceleration shows that even for low grade collisions it is possible for the head to reach acceleration levels approaching the magnitudes likely to cause cerebral concussion. Further work by Ommaya and others should enable useful advances to be made in this field.

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