ANALYSIS OF DIFFERENT HEAD AND NECK RESPONSES IN REAR-END CAR COLLISIONS USING A NEW HUMANLIKE MATHEMATICAL MODEL

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ABSTRACT

A study was carried out using detailed traffic accident data from rear-end car collisions involving Volvo cars. Vehicle and occupant related parameters influencing the risk of neck injury were identified.

A new humanlike occupant model was developed in Madymo-format comprising a mechanical equivalent of the complete spine. The motions of the occupant model were compared to volunteer data from a corresponding rear-end impact situation. The biofidelity of the model was found to be adequate for qualitative assessment of the influence of occupant and vehicle related parameters on the occupant response.

Conditions simulating some of the parameters identified in the accident study were tested in the occupant model. The parameters were: horizontal and vertical distance between head and head support, crash pulse and characteristics of the head support. The correspondence between the responses of the occupant model and the expected risk of injury was investigated.

Tensile and shear forces between adjacent vertebrae, head angular acceleration and "flow" of the lower cervical spine were found to best predict risk of injury in this model.

INTRODUCTION

Neck injuries in rear-end car collisions have been brought to an increased attention in recent years. Although having a low threat to life risk, these injuries can give long term consequences (Nygren et. al., 1984).

Influence of different parameters

Based on statistics, in-depth studies and biomechanical research, Carlsson et. al. (1985) showed, that the occurrence of neck injury in a rear end impact is dependent on several factors. Car related parameters, such as seat stiffness, horizontal and vertical distance between the head and the head support, as well as individual parameters, like sex, size, age, awareness of the impending accident and ability to withstand pain, are important factors.

A study by Nygren et. al. (1985), based on accident data concluded that the vertical position of the head support is important in reducing neck injuries in rear-end collisions.

Olsson et. al. (1990) presented results, based on an in-depth study, that a horizontal distance of more than 10 cm between the head and the head support correlates with an increased risk of neck injuries in rear-end car collisions. The duration of the neck symptoms seemed to be correlated with the extent to which the impacted car was deformed, making softer impacts (i.e. rear side members not engaged) at a given speed, less likely to result in injury.

Potential injury mechanisms

Aldman (1986) presented a hypothesis predicting that the volume changes inside the spinal canal, during a swift extension - flexion motion of the cervical spine resulting in transient pressure changes in the Central Nervous System, could induce injurious mechanical loads to the tissues inside the intervertebral foramina. Svensson et. al. (1993a) presented test results that corroborate Aldman's theory.

Ono et. al. (1993) used a sled test serie involving volunteers to point out that not only neck bending moments and head rotation angle but also the neck shear force and the axial force should be analyzed in relation to neck response.

Tools to simulate human response in rear-end car collision

A tool for simulating the motion of the human body during a rear-end impact is needed. Existing standard anthropometric test dummies, originally designed for frontal impact, have proved not to be biofidelic in rear-end impact testing (Scott et. al. 1993 and Szabo et. al. 1994).

Prasad et. al. (1975) developed a mathematical model with a more biofidelic spine. No other mathematical model comprising a complete spine for rear-end impact simulations was found.

A Rear Impact Dummy neck (RID-neck), to be used with the Hybrid III dummy, was developed by Svensson et. al. (1992). The RID-neck was shown to have improved performance regarding head-neck motion in rear-end impacts. However, the Hybrid III dummy does not have thoracic and lumbar spinal segments with adequate biofidelity for rear impact purposes (Svensson et al, 1993b). This has encouraged us to develop a mathematical model that models the motion of the human body in rear-end collisions.

OBJECTIVE

The aim of this work was to study the effect of different parameters on several possible injury related occupant responses by using a new humanlike mathematical model together with detailed traffic accident data. The correlation between the responses of the model and the expected risk of injury was to be determined.

ACCIDENT DATA

Method

All new Volvo cars, sold in Sweden, are covered by a three year damage warranty by the Volvia insurance company. About 10 % of these cars are involved in some kind of accident each year. Accidents in which the repair cost exceeds a certain level (currently > 25 000 SEK) are investigated by Volvia's insurance claim inspectors. Technical data about the damaged, together with accident, occupant, and injury data are collected for each car and stored in a computer data base. The injury data is gathered from medical injury reports and analyzed by a physician associated with Volvo's Accident Research Team. The present data base consists of about 20 000 accidents.

The object of this study was rear-end collisions which occurred during 1988-1989. Collisions involving secondary collisions or rollover were excluded. A total of 115 cars, mainly of Volvo 200 and 700 series, were selected. The total number of occupants was 163.

One to two years after the accident a questionnaire was sent to the 163 occupants as a complement to the primary standard analysis carried out directly after the accident. A total of 26 questions were asked in the questionnaire. Some of the questions addressed the sitting posture and awareness of the impending impact: sitting height, distance to the head support, kind of head support (with or without cushion), seat back inclination (before as well as after the impact), degree of support of the seat back (e.g. if the occupant was leaning forward or not), if the occupant had turned his body and/or his head to any side and if the occupant was prepared at the time of impact (e.g. tensed neck muscles). Questions concerning previous neck injuries and the state of neck injury (if any) induced by the accident, including questions about occurrence of injury, level of injury, duration and consequences were asked. The term injury comprises all kinds of discomfort and pain.

A statistical analysis was carried out to find parameters related to occurrence of neck injury. An in-depth study, of all cases where the occupant sustained a neck injury lasting longer than three month was also carried out.

Results

The study supported the observations made by Olsson et. al. (1990) stating that the risk of injury is correlated to increased horizontal distance between the head and the head support and also that the crash pulse influence the risk of injury sustained. Impacts involving stiff structures of the car, i. e. rear side members, showed an increased risk of injury compared to impacts of the same speed involving softer structures.

The possibility of sustaining a neck injury with long term consequences (more than three months) showed a significant correlation to the occupant having his head turned to the side at the time of impact. Increased seat back inclination before the impact as well as a stiff head support (absence of a comfort cushion) also indicated to be related to increased risk of neck injury.

None of the occupants who were aware of the impending impact and pushed themselves against the seatback and the head support were injured. This again shows that a short distance to the head support has a prominent effect on reducing the risk of injury. No difference in occurrence of injury could be seen between the occupants who were unaware of the impending accident and those who were aware and stretched their neck muscles and/or tightened their grip of the steering wheel without pushing themselves against the head support.

A conclusion from the in-depth study was that different individuals have different threshold levels for sustaining a neck injury with long term consequences. The data from this study indicated that, of a given severity, the occupants' tendency to sustain a neck injury was an important factor.

MATHEMATICAL MODEL

Description

The main feature of the model is that it comprises a mechanical equivalent of the complete spine in the sagittal plane. The model is implemented in Madymo 2D (TNO; 1992). A first version of it was presented in 1993 (Jernström et. al.). The model is shown in fig 1.

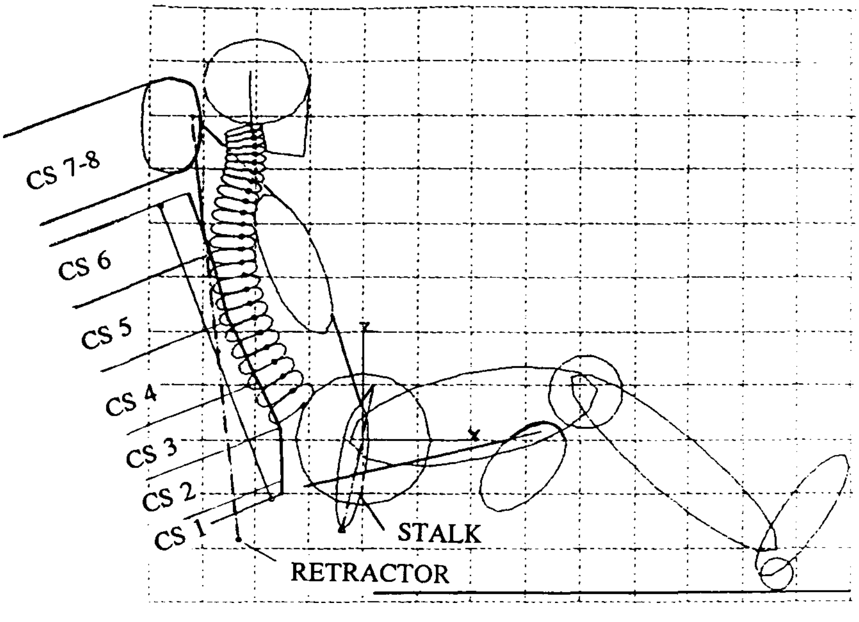


Figure 1. Madymo 2D rear-end collision model.
CS = Contact Surface

The AATD-50M drawing (Robbins; 1985), showing a side view of a mid-sized male adult, was used as a basis for the geometry of the modeled spine. The height of each of the 24 vertebrae increases linearly as a function of the distance from the occiput, making C1 the shortest and L5 the tallest. Adjacent vertebrae are connected by pin-joints.

The functions describing the bending torques for the joints (Fig. 2) are based on values from experimental studies (Osvalder; 1992 and Duserre; 1993) and adjusted to give realistic movements. When compared to values given by Prasad et. al. (June, 1974) a similarity can be seen (Fig. 2).

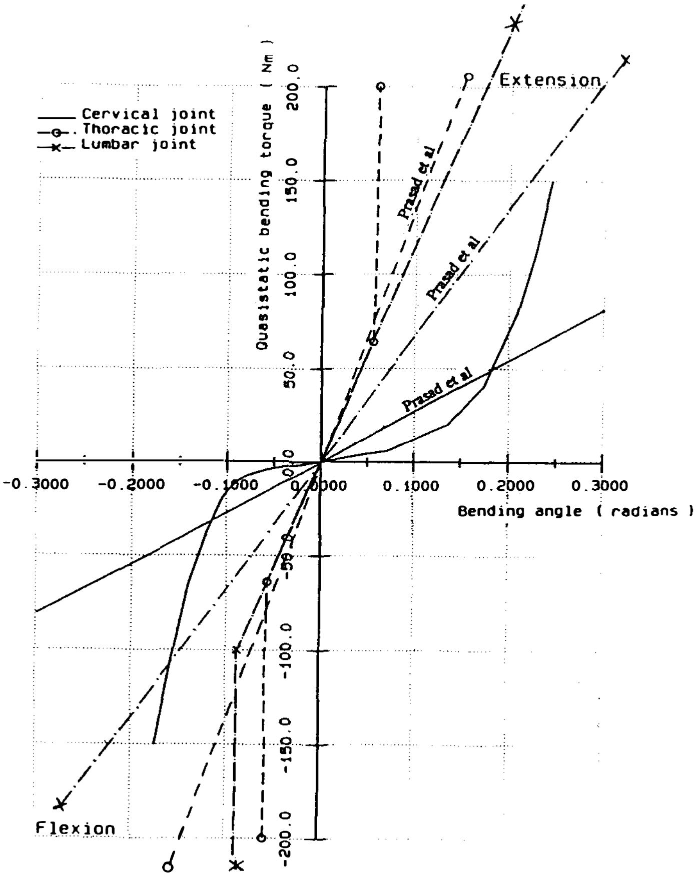


Figure 2. Diagram of the bending torques of the vertebrae joints

The effect of the safety belt was stated by McConnell et. al. (1993). Therefore, a body representing the rib cage and a standard 3-point belt, contacting this body and the pelvis, was incorporated. The rib-cage body was connected to the thoracic vertebrae by spring elements. The stiffness of the connecting springs was chosen so that it had no significant increasing effect on the bending stiffness of the spine. The tightening effect of the belt due to the rearward moving occupant is simulated by initially reducing the slack in the belt system.

The Madymo model seat was made up of eight contact surfaces (Fig. 1). The seat back comprises six surfaces and interaction with the nearest spinal elements was defined for each surface. The head support comprises two coinciding surfaces, one defining the interaction with the neck elements and one defining the interaction with the head. The characteristics chosen can be seen in Fig. 3. The seatback is articulated at a point close to the reclining mechanism. The chosen bending torque characteristic of the reclining mechanism can also be seen in fig 3.

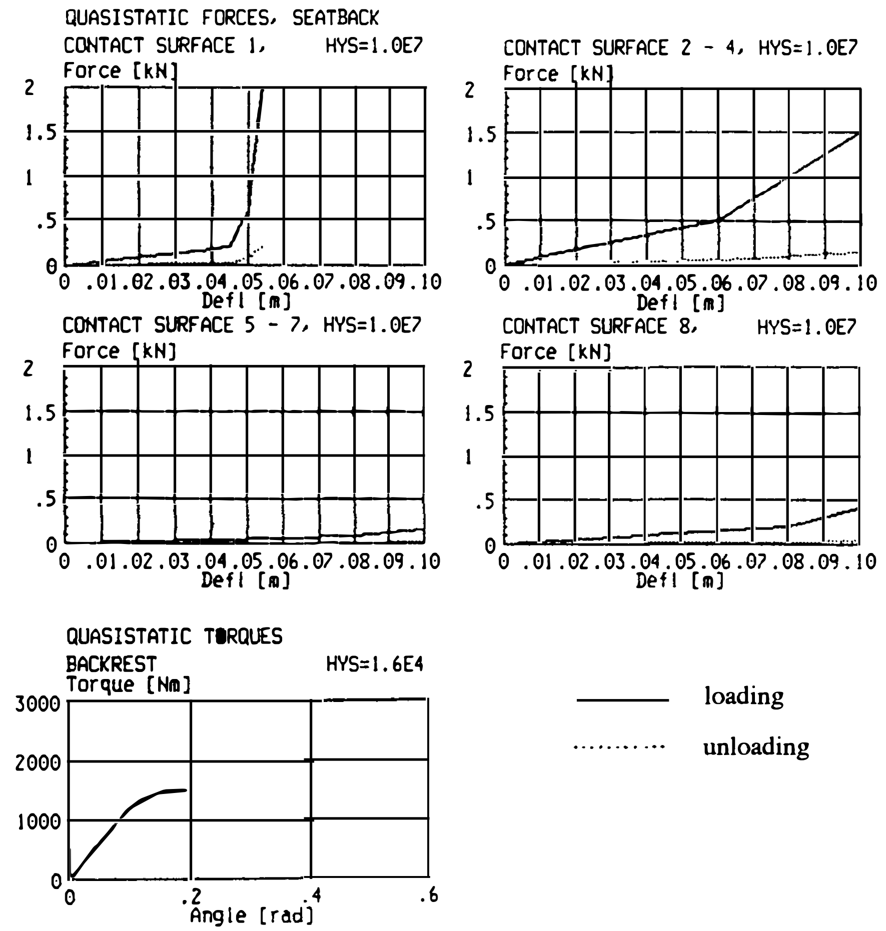


Figure 3. Characteristics of the seat back and the bending torque of the reclining mechanism.
Contact surface (CS) as illustrated in Fig. 1.

Validation of the model

To evaluate the movements and the responses of the model as a whole, it was run under conditions similar to volunteer tests published by McConnell et. al. (1993).

In the evaluation simulation the geometries of the seat and the head support of the model corresponded to those of McConnell. The curvature of the upper thoracic part of the spine appears to differ between the volunteer and the Madymo occupant model. The volunteer seems to contact the seat back at a higher point than the occupant model.

The rear-end collision pulse used in the validation test is similar to the pulse used by McConnell with a DeltaV of 7.83 km/h. The acceleration pulse is achieved by assuming an acceleration value at a certain time-step, integrate and then compare with the corresponding velocity value in the diagram presented in the paper by McConnell.

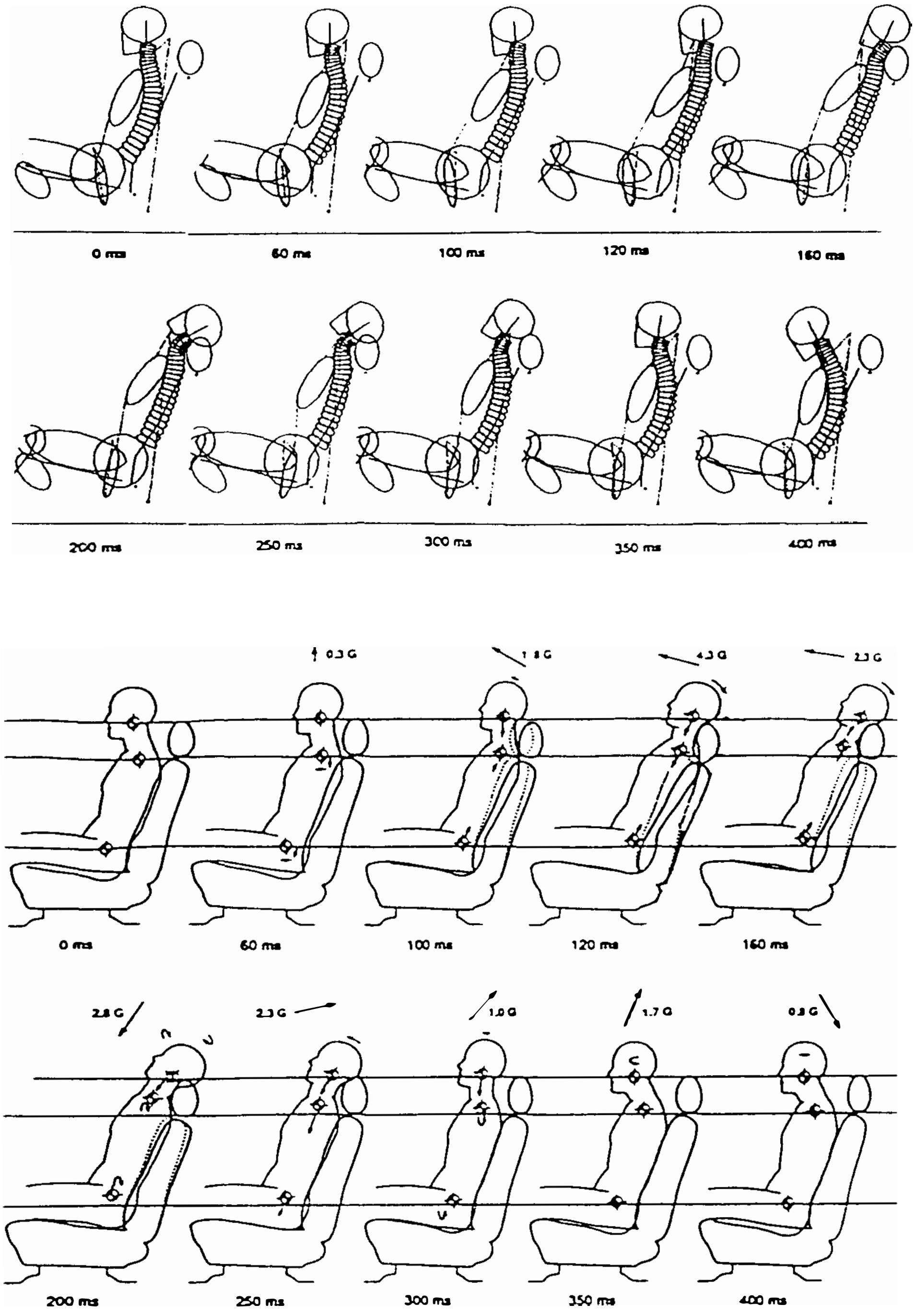


Figure 4. The Madymo occupant model compared to a volunteer from a corresponding rear-end impact situation (McConnell et. al.; 1993)

As can be seen in Fig. 4, the movements of the occupant model are similar to those of the volunteer, except for a certain time delay. Head support contact occurs at approximately 160 ms for the occupant model and 120 ms for the volunteer. The head support contact with the Madymo occupant model occurs at a lower level of the neck. The maximum angular head displacement appears to be somewhat larger for the model compared to the volunteer. The differences can be explained by the differences in seat characteristics and the differences in mechanical properties between the volunteer and the occupant model.

The biofidelity of the model was considered to be adequate for qualitative assessment of the influence of vehicle and occupant related parameters on the occupant response.

Parameter study

A study, regarding the influence of different occupant and vehicle parameters, was carried out using the Madymo occupant model. The primary aim of the study was to find which occupant responses best correlate to expected injury risk.

The study comprised one reference test plus five tests with changed conditions. As the reference test (no. 1) a seat with the geometry and characteristics close to a Volvo seat was modeled. The characteristics were chosen in accordance with Fig. 3 and can be considered as having a good energy absorbent capacity. The reference pulse was a rear-end impact resulting in a DeltaV of 11,2 km/h, engaging rear side members. The acceleration pulse is shown in Fig. 5.

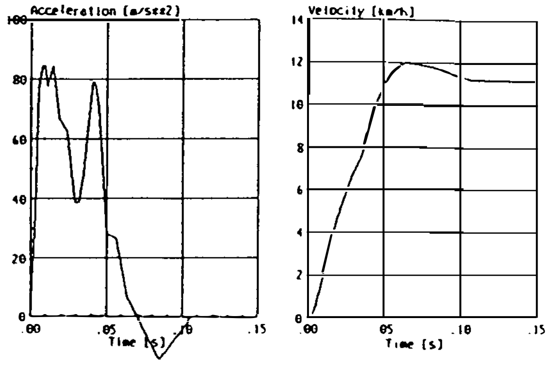
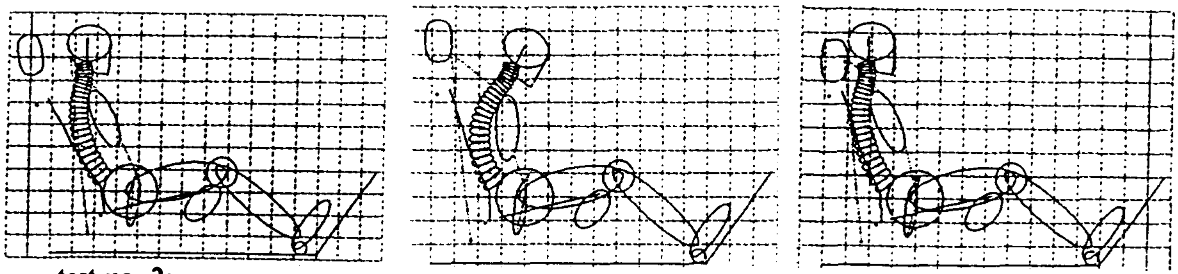


Figure 5. Acceleration pulse of tests no. 1 - 5.

It was expected that the conditions in tests no. 2-6 would be related to the risk of neck injury. The expected relationship to the risk of injury was based on earlier studies as well as on the detailed accident data presented previously. Tests nos. 2 - 5 were expected to give an increased risk of injury and test no. 6 a decreased risk of injury. The parameters varied were represented by the modifications shown in Fig. 6.

The following output responses were studied in order to arrive at the best possible prediction of neck injury risk in the model:

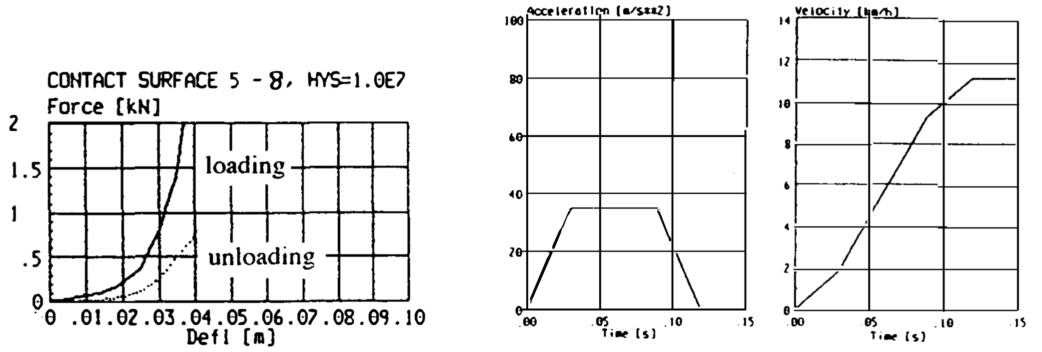
- Resultant torque (My), tensile force (Fz) and shear force (Fx) measured between the head and C1 and between T1 and T2.
- The time derivative of the volume inside the spinal canal as a function of time, "flow", of the upper and lower part of the cervical spinal canal. The volume change rate is proportional to a flow of veinblood which in turn is related to a flow velocity and a pressure gradient for a given vessel system (Svensson et. al.; 1993a). A pressure gradient of this type was suggested to be the cause of nerve injury in the cervical nerve root region (Aldman; 1986 and Svensson et. al.; 1993a).
- The extension angle of the head relative to the torso
- Linear acceleration of occiput in x- and z-direction, respectively
- Resultant head angular acceleration



test no. 2;
seatback inclination increased by 10 degrees

test no. 3;
the occupant is leaned forward by increasing the vertebra angles in the lumbar spine

test no. 4;
head support lowered, allowing the head to rotate above it



test no. 5;
simulating absence of comfort cushion; stiffer and less energy absorbing head support and upper part of seatback

test no. 6;
acceleration pulse simulating softer impact; pulse with reduced g-level, DeltaV unchanged

Figure 6. Parameters varied in tests no. 2 - 6

Results

The output responses and the motions of the Madymo dummy are presented in appendices 1 and 2.

Tests nos. 2 - 6 were compared to the reference test by comparing the magnitude of the first 300 ms of the responses. A higher magnitude in test no. 2 - 6, in comparison to test no. 1, was rated more severe (+) and a lower magnitude as less severe (-). Equal severity was rated 0. The rating is presented in Table 1. No effort was put into ranking the output responses since the simulated modifications were quantitatively incomparable. By rating the responses into three classes (+, - and 0) the trend of which of the occupant responses that were most consistent was determined. The consistent responses are then accordingly assumed to be correlated to the expected risk of injury.

anticipated severity		increased				reduced
response	test	no. 2 seatback inclined	no. 3 forward leaning	no. 4 lower headrest	no. 5 absence of comfort cushion	no. 6 softer acc-pulse
torque	head/C1	-	+	-	+	-
	T1/T2	+	+	+	0	0
shear force	Head/C1	+	+	+	+	-
	T1/T2	+	+	+	0	-
tensile force	Head/C1	+	+	+	+	-
	T1/T2	+	+	+	+	-
flow	upper	0	+	-	+	-
	lower	+	+	+	+	-
occiput acc.	x	0	-	-	+	-
	z	+	+	0	0	-
head extension		-	+	-	0	-
head angular acc.		+	+	+	+	-

Table 1. Output occupant responses in tests no. 2 - 6 related to reference test no. 1; "+" = more severe, "-" = less severe and "0" = equal severity

Shear force, tensile force, the head angular acceleration and the volume change rate ("flow") of the lower neck turned out to have good correlations with the expected injury risk.

Torque (My), linear acceleration, extension angle and volume change rate ("flow") of the upper neck turned out not to have so consistent responses to the expected risk of injury.

DISCUSSION

Accident study

In the detailed accident data presented in this work as well as in previous studies, the chosen parameters in the simulation study (increased vertical and horizontal distance between head and head support, absence of a comfort cushion in the head support and reduced crash pulse) have shown to be related to risk of sustaining a neck injury in rear-end impact. However, the accident data did also indicate that risk of sustaining a neck injury, especially with long term consequences, is related to each individual's threshold of sustaining an injury, as well as parameters of how the occupant is sitting at the moment of impact, e. g. if the occupant is turning his head to the side.

Mathematical model

The new Madymo occupant model was considered to be an adequate tool for simulating occupants in rear-end impacts. The spine comprised of individual vertebrae enabled the movements to be humanlike as indicated by the validation.

Adjacent vertebrae were connected by pin-joints. The validity of this has been discussed. Prasad et. al. (June and Sept, 1974) stated that the joints should be described by a more complex relationship since it is possible that the location of the centre of rotation between adjacent vertebrae is a function of the type of load the two bodies are exerted for. This could be a modification to consider in the future. The present occupant model has shown to be appropriate for this study.

The effect of muscular tonus has been incorporated into the quasistatic bending torques of the vertebral joints. The time-dependency of the musclereflexes has not been considered. Thus the functions are probably too stiff for the first 70-80 ms of the crash event, when simulating an unaware occupant. If implemented into Madymo 3D it would be possible to consider the time-dependency.

Influence of parameters

A ramping motion of the torso up along the seatback as well as a straightening of the spinal curvature during the forward acceleration of the torso leading to a head elevating motion was seen in all of the tests. This was also experienced in tests with volunteers performed by McConnell et. al. (1993). When the head support was lowered, test no. 4, this elevating motion increased the bending of the head above the top of the head support. When designing head supports this head elevating effect should be taken into account in order to make sure that the head is not bent over the top of the head support.

In the accident study an additional cushion (designed for comfort rather than for safety) which can be found in some cars, turned out to have a positive effect on the risk of sustaining a neck injury. Even though this cushion has a limited energy absorption it indicates the effect of favourable characteristics. Making the head support, and also the seat as a whole system, energy absorbing is a design parameter to take into account.

At the same DeltaV, a crash pulse with a lower g-level, compared with a higher g-level, turned out to have a reduced effect on almost every response calculated. The accident data showed that this is a parameter to consider when designing the rear-end structure of cars.

Injury mechanisms

Forces (Fx, Fz) in the occipital- and the T1/T2 joint as well as the angular acceleration of the head turned out to have good correlation to expected risk of injury in the situations tested.

According to the hypothesis of Aldman (1986) the risk of injury to the cervical nerve root region is related to the pressure gradient between the inside of the cervical spinal canal and the ambient soft tissue. This pressure gradient is in turn dependent upon the velocity and acceleration of the flow of vein blood across the intervertebral vein bridges (Svensson et. al., 1993a). In the present study the flow correlated to the expected injury risk in the lower cervical spine but not in the upper cervical spine. This result is in line with the findings of Svensson et. al. (1993a) where it was found that the pressure generated by the motion of the lower cervical spine superimposes on, and appears to override the influence of, the pressure generated in the upper cervical spine. It should be noted that the "flow" does not directly correspond to the pressure gradient between the inside of the cervical spinal canal and ambient soft tissue, since it does not take into consideration the acceleration of the flow and the non-linear relationship between the flow and the corresponding pressure component. The pressure gradient build-up during the flexion-extension motion of the cervical spine is, in other words, too complex to be captured correctly by this model.

Neck injuries in rear-end collisions may result from several different mechanisms. Head supports were included in all our tests restricting the head motion and excluding the hyperextension of the complete cervical spine as a cause of injury. It is possible that head extension angle and torque could turn out to be better correlated to risk of injury if bigger relative motions between head and torso are allowed.

CONCLUSIONS

By using parameters known to effect the risk of injury sustained in rear-end car collisions and relating them to possible injury related responses, using a humanlike mathematical model, some probable mechanisms have been pointed out. Forces between adjacent vertebrae as well as angular acceleration of the head and "flow" of the lower cervical spine turned out to have the best correlation to expected risk of injury.

APPENDICES

Appendix 1: Diagrams of output responses from test nos. 1 - 6 (2 pages)
Appendix 2: Motions of the Madymo occupant model in test nos. 1 - 6 (2 pages)

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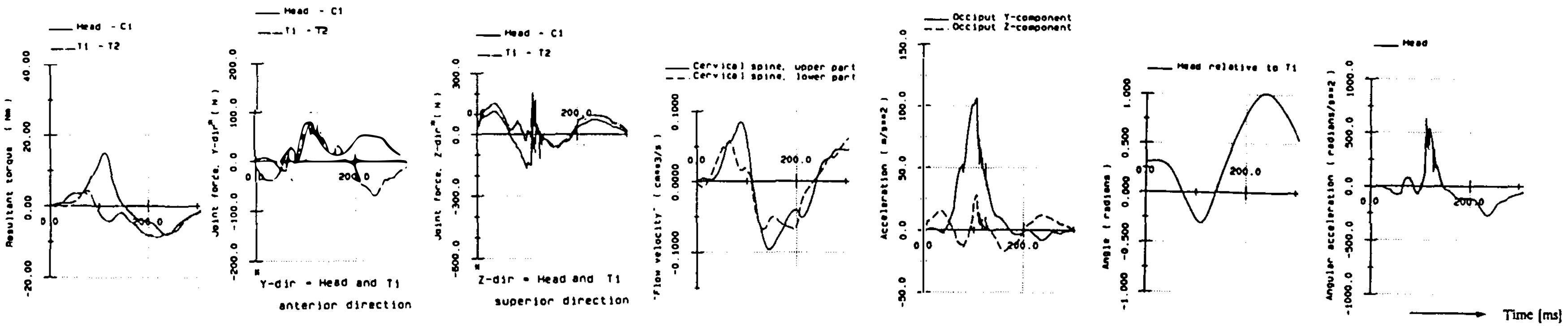
Test number 1



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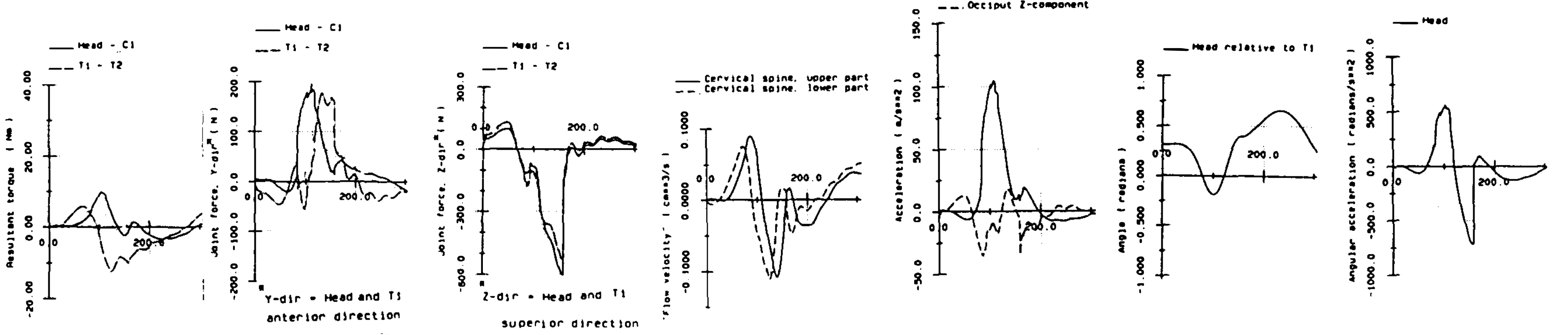

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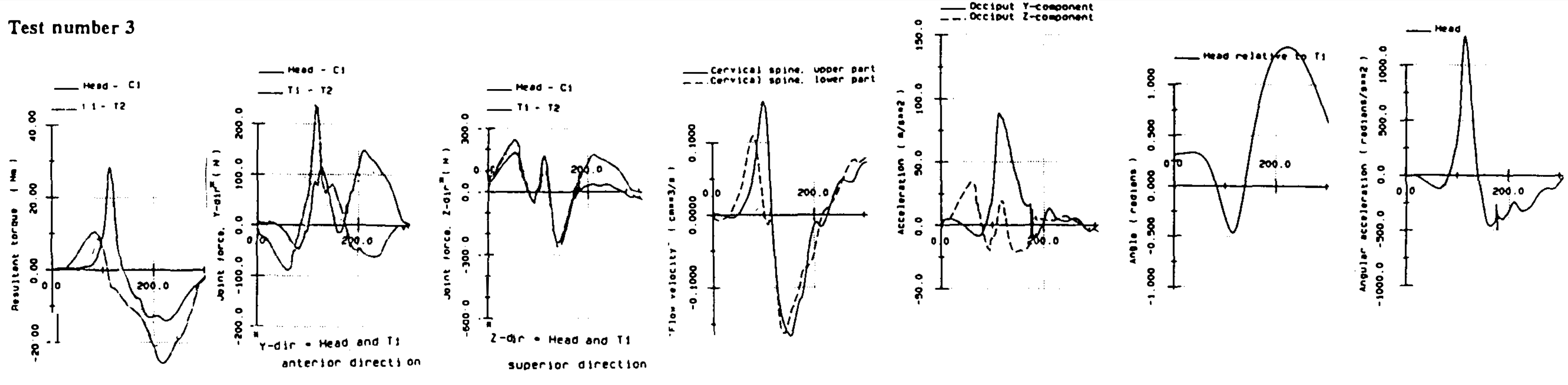

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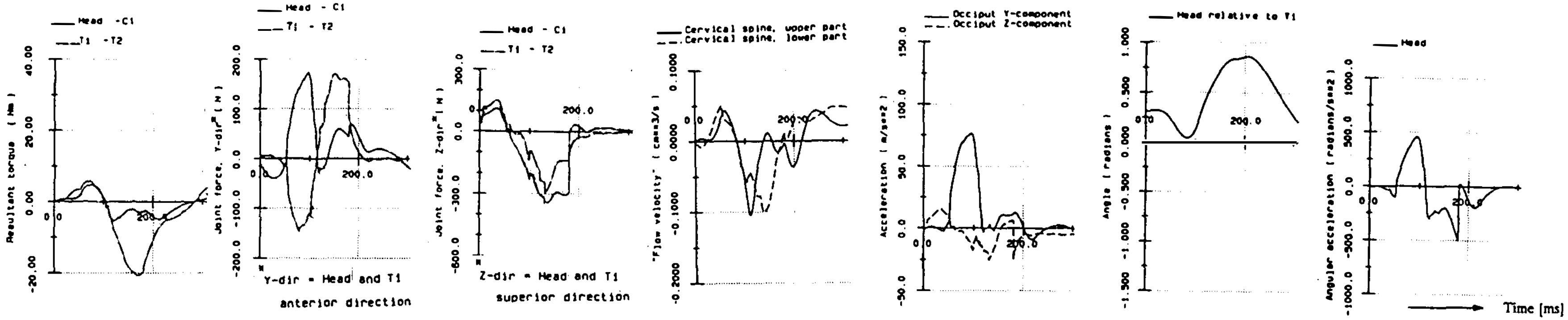

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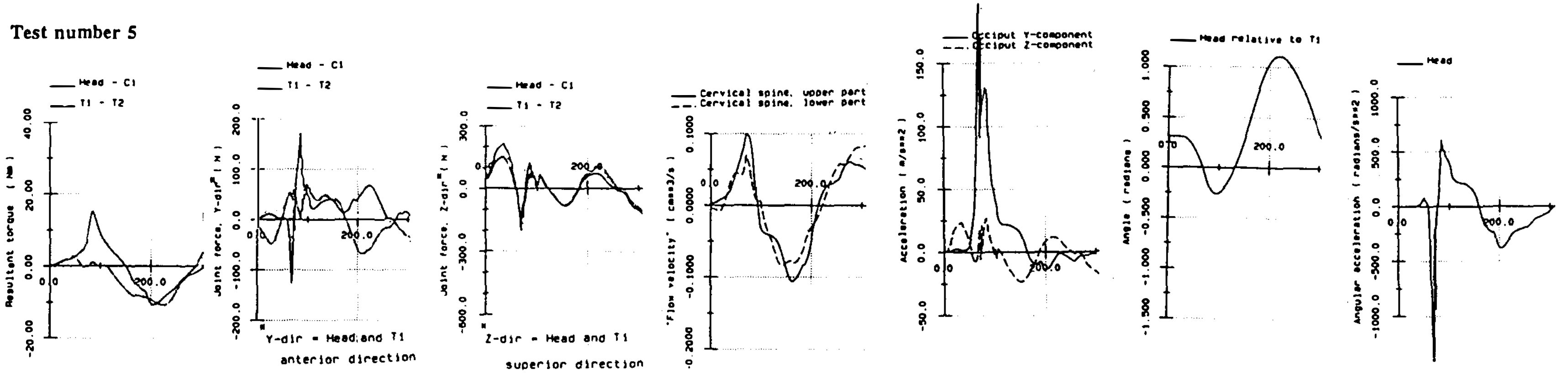

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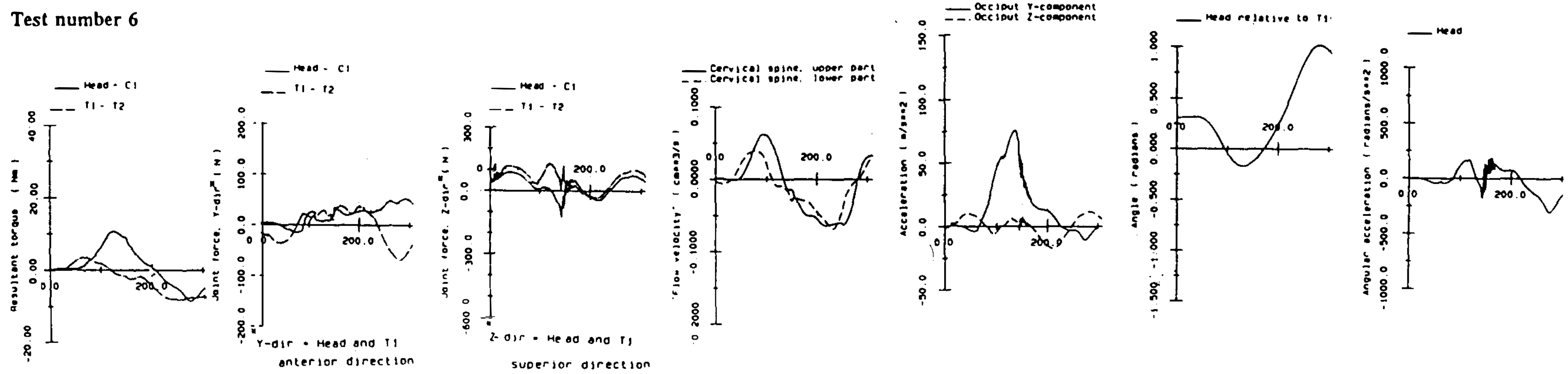
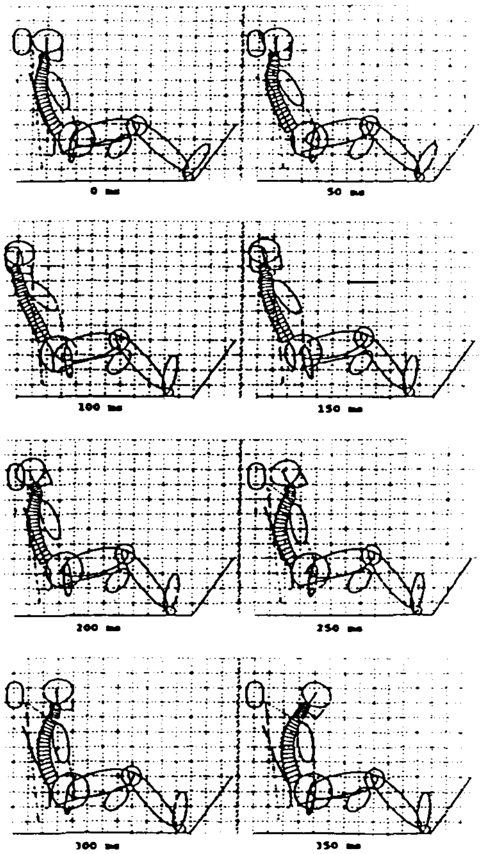
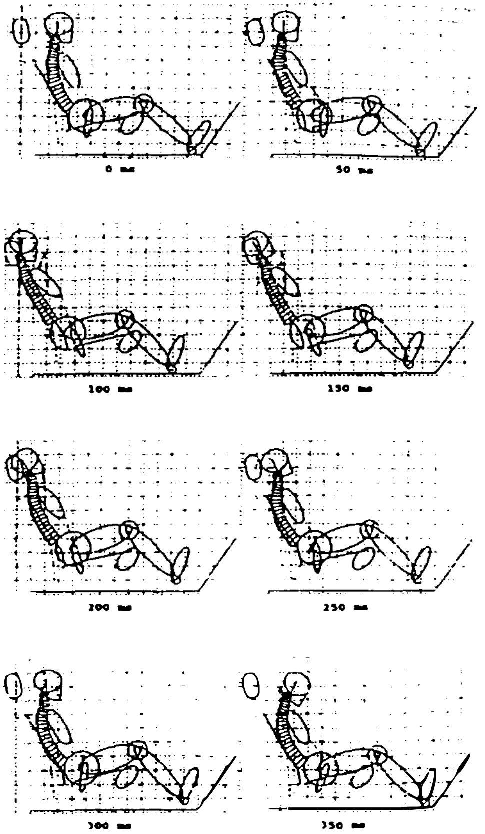


VOLVO TEST NO. 1 - reference test



VOLVO

TEST NO. 2 - increased seatback inclination



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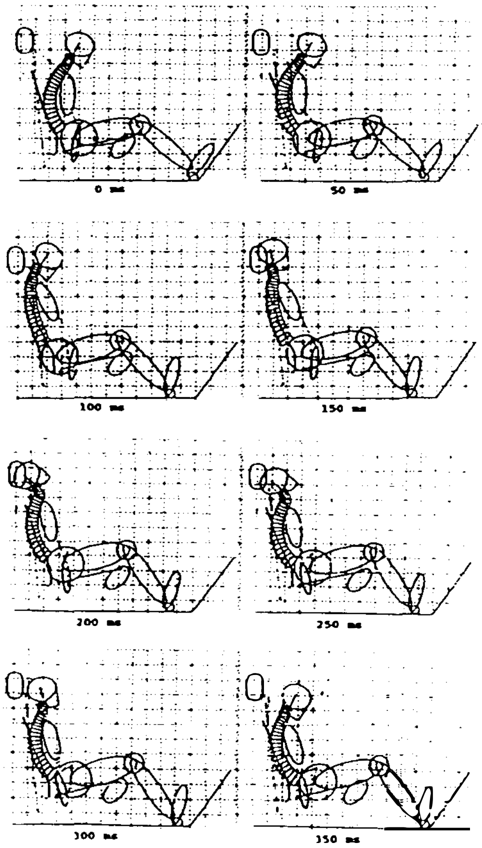
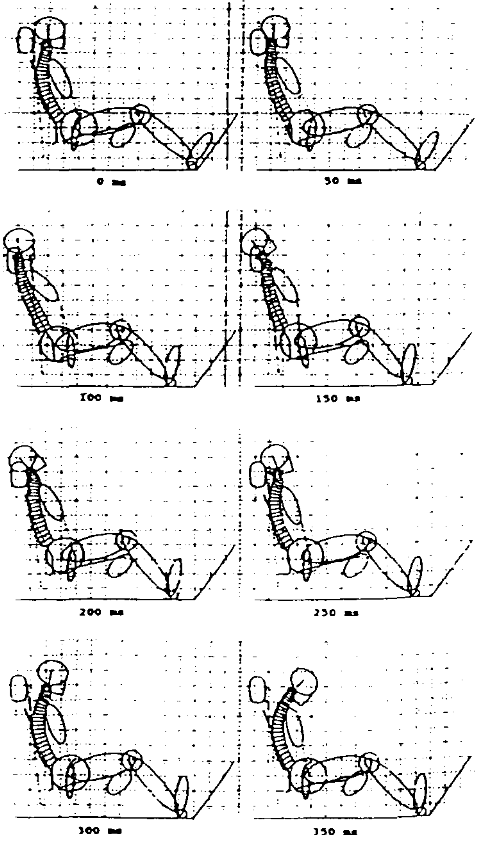
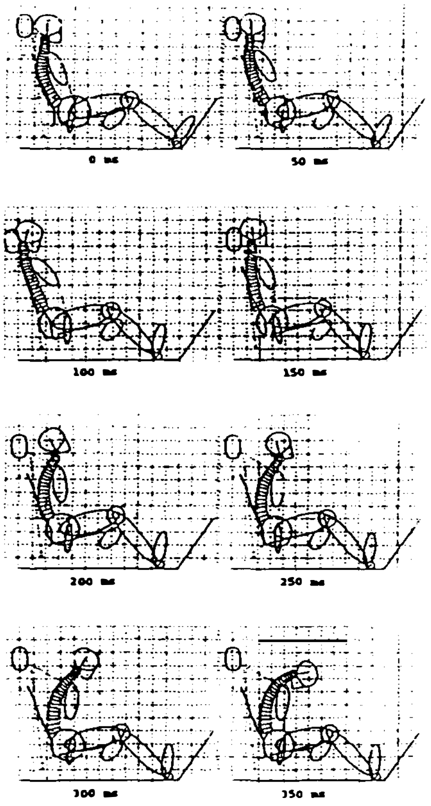


VOLVO TEST NO. 4 - headrest lowered



VOLVO TEST NO. 5 - absence of comfort cushion



VOLVO TEST NO. 6 - softer acceleration pulse