A DUMMY FOR REAR-END COLLISIONS: DEVELOPMENT AND VALIDATION OF A NEW DUMMY NECK

A Dummy for Rear-End Collisions -

Development and validation of a new dummy-neck.

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ABSTRACT

A new dummy-neck for rear-end collision testing has been developed and validated. The effectiveness of passenger car head-rests in rear-end collisions remains poor and whiplash-injuries, often occurring at low impact-speeds, are a great problem. Until now, there has been no acceptable dummy for rear-end impact testing. The new neck consists of seven cervical and two thoracic vertebrae connected with pin joints and is designed solely for rear-end collision-testing at low impact-speeds(<20km/h). It was validated with a series of volunteer tests and showed good accordance. A Hybrid III-neck was tested under the same conditions and proved to be too stiff and appeared to have too high resistance to horizontal translational motion between head and torso.

INTRODUCTION

Whiplash injuries[1] usually occur in rear-end impacts at low impact velocities, typically less than 20 km/h (States et al., 1972; Kahane, 1982; Romilly et al., 1989). The protective effect of the head-restraints is small, typically 20% (O'Neill et al.,1972; Huelke and O'Day, 1975; Nygren et al., 1985). States et al. (1969) presented a theory saying that the timing of the elastic rebound of the seat-back in a rear-end collision can be such that the torso is pushed forwards in the passanger compartment while the head is still moving backwards. This would increase the relative velocity between the head and the torso and thus increase the risk of neck injury. Later studies support this theory (McKenzie and Williams, 1971 ; Prasad et al.,1975 ; Rommily et al., 1989 ; Foret-Bruno et al., 1991). There is a general difference in design between front- and rear-seats in passenger-cars. The seat-back of the rear seat is generally less elastic and several authors have reported a considerably smaller risk of neck-injury in the rear-seat compared to the front seat for adult car occupants (Kihlberg, 1969; States et al., 1972; Carlsson et al., 1985; Lövsund et al., 1988; Otremski et al.,1989). Nygren et al. (1985) found that the risk of getting a whiplash injury was not reduced in newer cars. The study disclosed great differences in protective performance between different car models.

Today, there is still no adequate method for testing the protective effect of seats and head-rests of passenger cars in rear-end collisions. A method for testing car seats in simulated rear-end collisions is needed to improve the protective performance of head-rests and seat-backs. The best available dummy at present is the Hybrid III. The spinal structure of this dummy is extremely rigid and is unlikely to interact with the seat-back in the same compliant way as the human spine.

Seemann et al. (1986) found that the Hybrid III neck is much too stiff to respond in a human-like manner in the sagittal plane. Deng (1989) reported that results from a mathematical

[1] In this paper, **whiplash motion** is defined as the motion of the head and neck, relative to the upper torso, that occurs if the torso is accelerated forwards and the head and neck lag behind due to their inertia. The neck will be forced into extension and the head will rotate backwards. This rearward head neck motion will finally be stopped by the structures of the neck and in some cases also by the contact between the head and a head-restraint. Hereafter the head and neck will move forward and return to its initial position and might finally go into flexion. The flexion part of the motion is generally much less violent than the flexion motion that is seen in frontal collisions.

model of the Hybrid III neck indicated that the neck has a torque response similar to that of the human neck but has a higher shear response. Foret-Bruno et al. (1991) compared the Hybrid III dummy with a cadaver in simulated rear-end impact using a head-rest closely fitted to the head to minimise the relative movement between head and torso. The cadaver showed no sign of injury. In spite of this, very large shear forces at occipital level were registered in the Hybrid III test. The authors concluded that the human head can be moved relative to the torso without any stresses in the neck but this is not the case for the dummy.

Experience from ongoing experiments at our department on anaesthetised pigs indicate that the resistance of the neck to static displacement is small for motion in the sagittal plane, within the range of voluntary motion, when all muscle tone is eliminated. Under dynamic conditions, however, the damping properties of the pig-neck appeares to have a considerable resistive effect on the simulated whiplash-motion. For a human, a certain muscle tone is required to balance the head. When sudden motion of the cervical spine is enforced by external forces, muscle reflexes increase the tension of the cervical muscles and the resistance to the motion is sharply increased (Foust et al., 1973). These muscle reflexes had a delay of 56-92 ms and the peak deceleration during inflicted extension motion occurred after 115-151 ms (Foust et al., 1973).

The aim of this study was to develop a dummy-neck for low velocity (<20km/h) rear-end collisions and validate it with results from volunteer tests. The new neck was intended as a replacement for the original Hybrid III-neck when working out guide-lines for the design of future seat-backs / head-rests

MATERIALS AND METHODS

Neck

A new neck, to be used on the Hybrid III dummy in rear-end collision testing, was designed. It consists of seven cervical and two thoracic vertebrae and was designed to resemble the human anatomy in order to enable a trajectory of motion, in the sagittal plane, similar to that of the human (Fig. 1). The neck was given the name "RID-neck" (Rear Impact Dummy - neck).

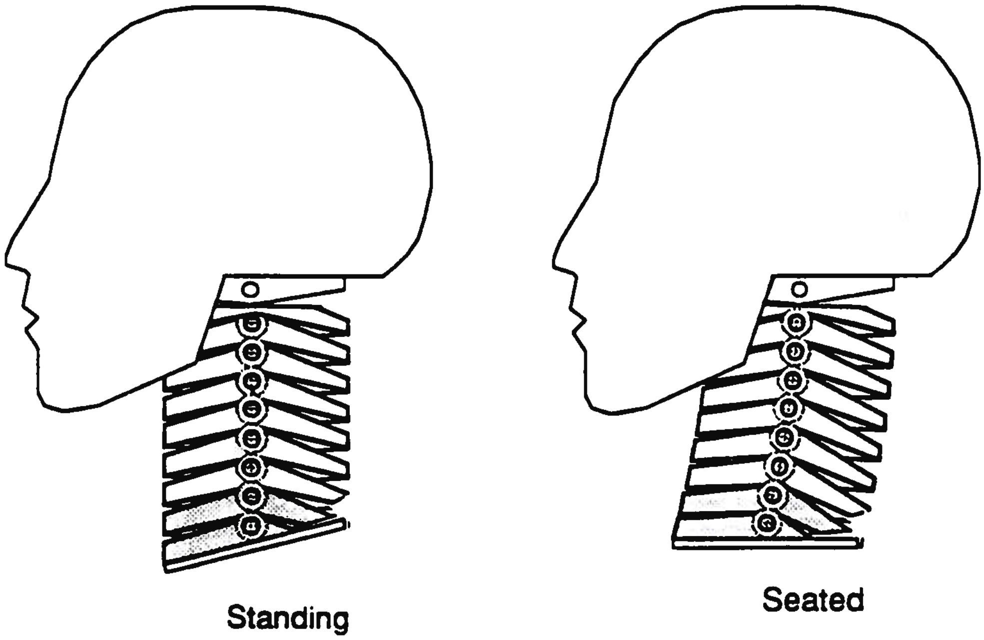

Figure 1: The RID-neck with a Hybrid III head. Standing posture and seated posture. In the seated posture the neck is flexed 14°.

The vertebrae are made of acetal plastic and are connected with pin joints. All the vertebrae are of the same height, 16mm (Figure 2). The cervical vertebrae and the occipital joint, all have the same angular range of motion, 10° in extension and 5.6° in flexion, relative to the nearest inferior vertebra. The first thoracic vertebra has an angular range of motion of 3° extension and 3° flexion relative to the second thoracic vertebra which in turn is fixed to the upper torso of the dummy. This gives the neck a total angular range of motion of 83° in extension and 48° in flexion (0° of flexion-extension is here defined as the neck-posture of a person standing upright with the head kept horizontal).

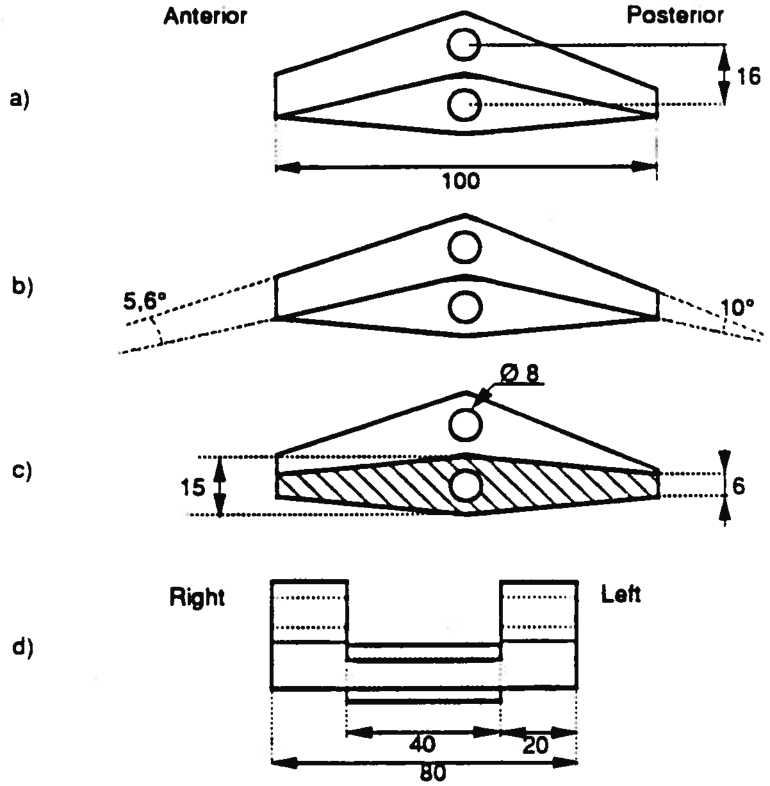

Figure 2: Coarse drawing of a RID-vertebra, side view (a, b), sagittal cross-section (c) and frontal view (d) (dimensions in [mm])

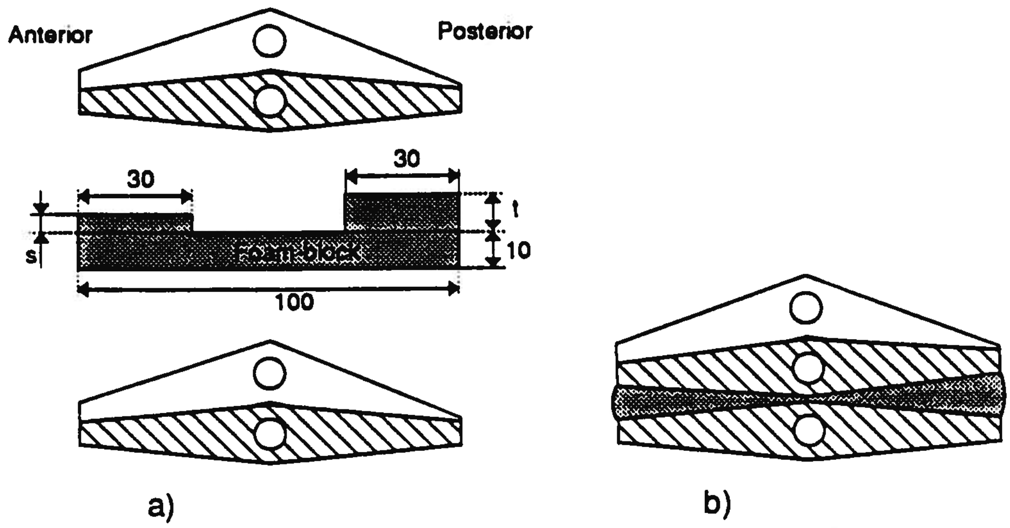

Figure 3: Sagittal cross-section of two adjacent RID-vertebrae with intervening foam-block, before assembly (a), and after assembly (b) (dimensions in [mm]).

The lordosis of the human neck, in standing posture, has not been taken into account. Thus, this neck is straight in standing posture and has a slight kyphosis in seated posture (Figure 1).

The interspaces between the vertebrae are filled with blocks of Neoprene plastic foam (hardness: Shore 00=60, Shore A=15) (Figure 3). Each foam-block is glued to the inferior vertebra with double-sided adhesive tape and can easily be replaced in order to change the mechanical properties of the neck. In all the tests in this study, the stiffness was chosen to be constant along the whole neck.

The flexion angle between torso and head is normally 14° for the seated Hybrid III dummy. Thus, the foam blocks were made thicker on the posterior (rear) side of the neck, compared to the anterior (front) side (Figure 3), to give the RID-neck a 14° flexed seated posture at rest (Figure 1,b). Each joint of the neck is thus flexed approximately 1.6°.

Validation testing

The validation tests were done with a Hybrid III calibration pendulum (Fig. 4) (General Motors Co., 1984). The RID-neck was tested with three different thicknesses of the foam-blocks (Table 1). A Hybrid III-neck was also tested under the same conditions for comparison. Each test was repeated three times.

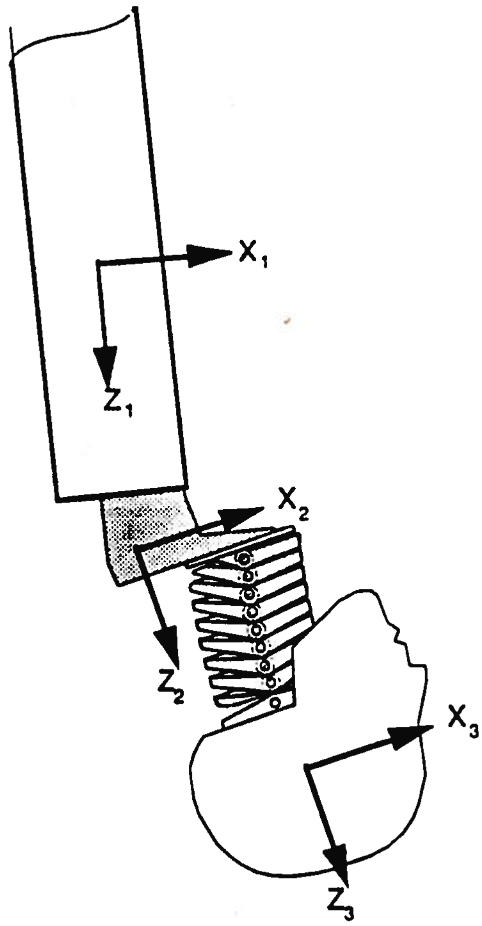

Figure 4: The RID-neck, with a Hybrid III head, mounted in a Hybrid III calibration-pendulum.Three coordinate systems were introduced, the first (X_1,Z_1) has the Z-axis parallel to the pendulum, the second (X_2,Z_2) has the X-axis parallel to the horizontal plane of the lower neck and the third (X_3,Z_3) is fixed to the head.

The mean acceleration pulse of the pendulum was set to about 25 m/s^2 and the pre-impact velocity to 3 m/s in order to resemble the test conditions used in a test series with volunteers (Tarriere and Sapin, 1969). The pendulum test set-up was instrumented with accelerometers, one on the pendulum in X_1-direction and one three-axial in the dummy head. Force- and moment-transducers were used at the occipital joint and in the lower neck. The tests were also high-speed filmed at 500 frames per second.

The lower-neck transducer has a fixed 14° flexion angle resulting in an angle of 14° between the pendulum and the head and neck (Figure 4). Three different coordinate-systems were introduced according to Figure 4 .

The high-speed films were digitised and 9th degree polynomial curve-fits were made from the angular-displacement data of the head. From these curve-fits, approximate angular velocity and angular acceleration of the dummy-head were calculated.

Table 1: Foam-block dimensions for the three different stiffnesses of the RID-neck. The thicknesses (s) and (t) are defined in Figure 3 and (w) is the width.

	s (mm)	t(mm)	w (mm)
RID 1	0	5	35
RID 2	0	5	40
RID 3	5	10	40

RESULTS

The extension angles as a function of time, for the pendulum tests, are compaired to the results from the volunteer tests (Tarriere and Sapin, 1969) (Figure 5). The maximum extension angles are shown in Table 2. The three RID-configurations show a common pattern of motion which differs from the pattern of the Hybrid III-neck for which the angular motion starts more abruptly and the resistance to flexion is much greater.

Figures 6 and 7 show angular velocity and angular acceleration of the head calculated from 9th-degree polynomial curve-fits. The general trend for the angular motion was that both velocity- and acceleration-levels increase with decreased neck-stiffness. Figure 8 shows the linear displacement of the head-CG (Centre of Gravity) in X_2-direction and Table 2 shows the maximum values. The RID-configurations show a common pattern contrasted by the Hybrid III which shows a higher resistance to forward displacement.

Table 2: Maximum extension angles and rearward head-displacements (X_2-direction) in the pedulum tests.

Neck	RID 1	RID 2	RID 3	Hybrid III
Angle (deg)	82	73	59	36
X_2-Displ. (m)	-0.159	-0.149	-0.134	-0.84

The occipital torque is shown as a function of extension angle (Figure 9). The peak-levels for the occipital torque increase with decreased neck-stiffness. The response-envelope for neck-extension, proposed by Mertz and Patrick (1971), is also included in Figure 9.

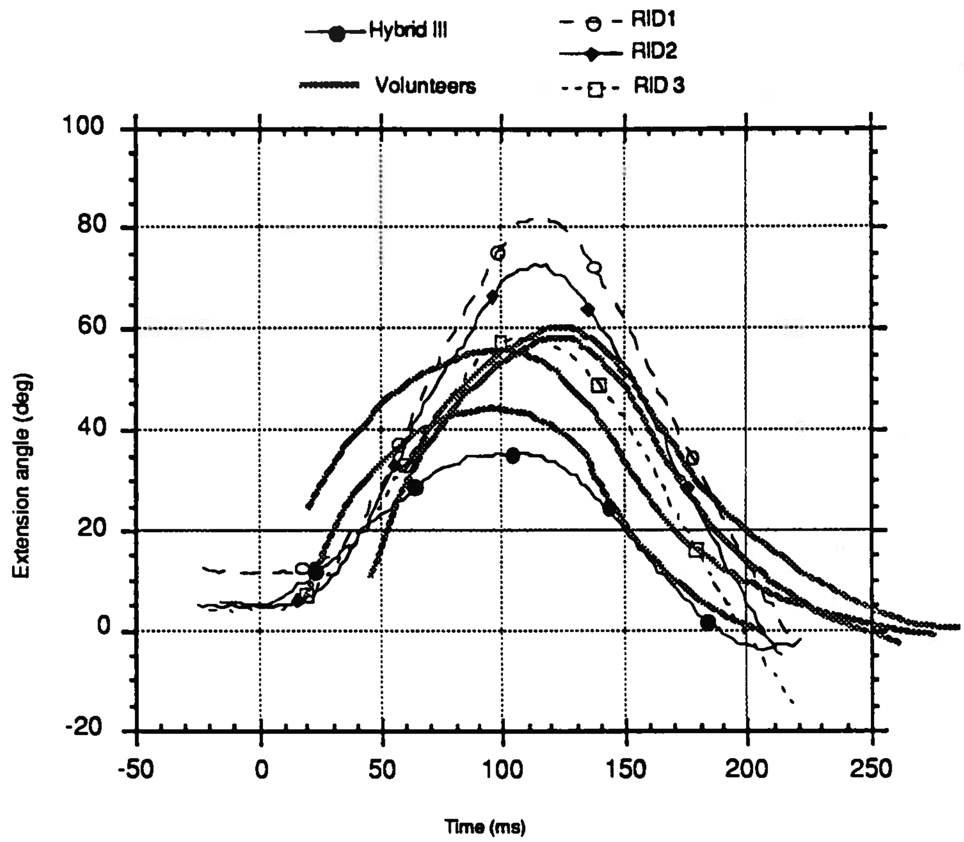

Figure 5: Extension angle for the pendulum tests and for the volunteer tests (Tarriere and Sapin, 1969).

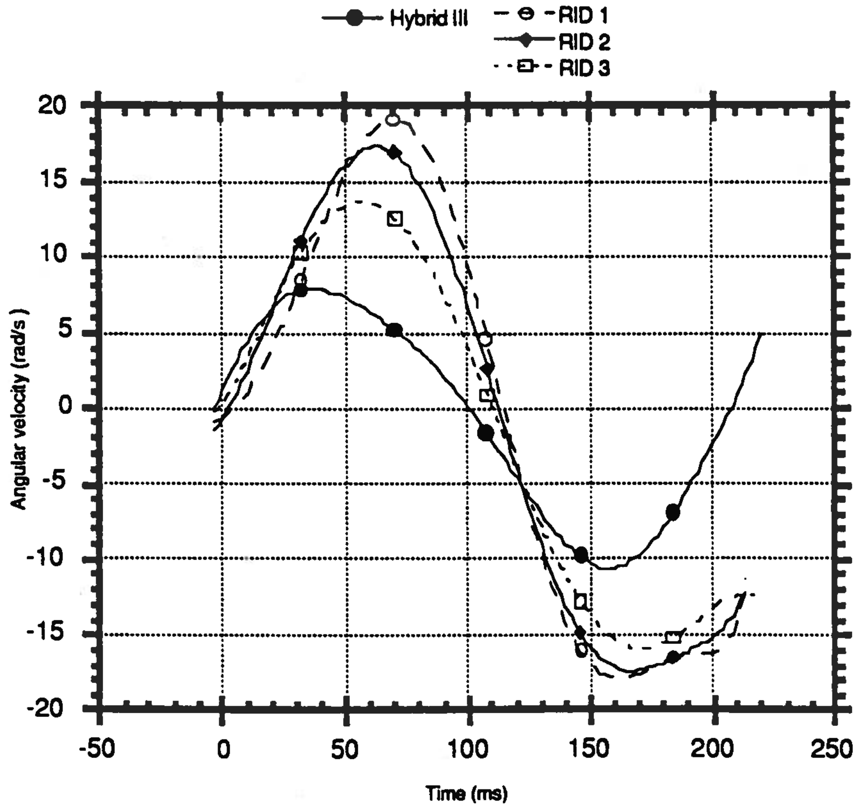

Figure 6: Angular velocity of the head relative to the pendulum, calculated from 9th-degree polynomial curve-fits of the results in Figure 5.

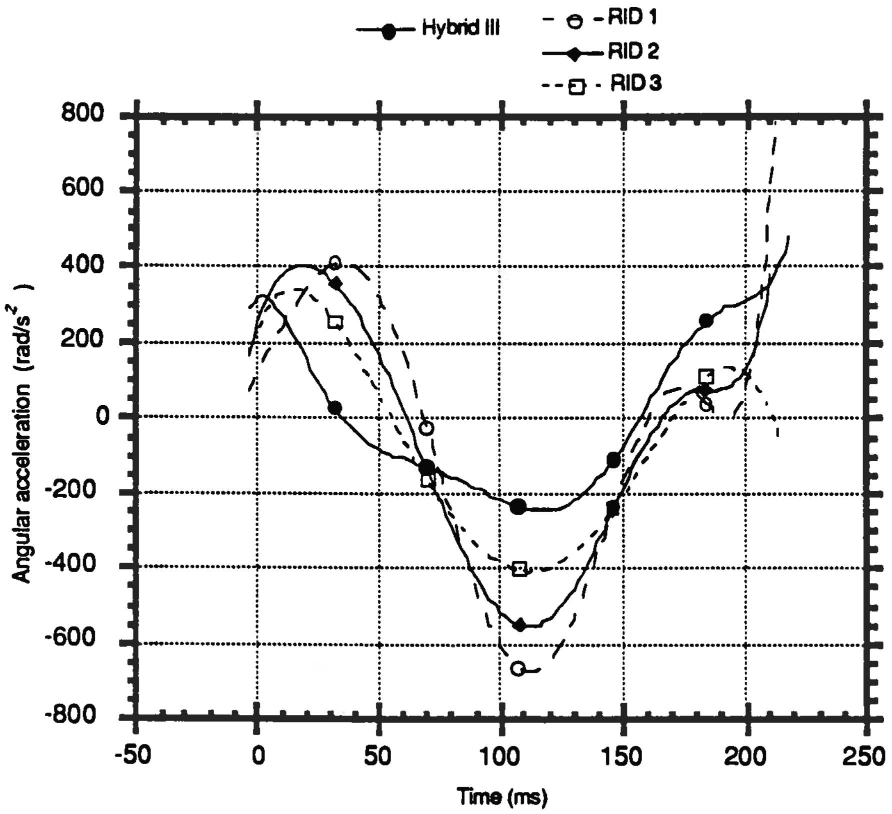

Figure 7: Angular acceleration of the head relative to the pendulum, calculated from 9th-degree polynomial curve-fits of the results in Figure 5.

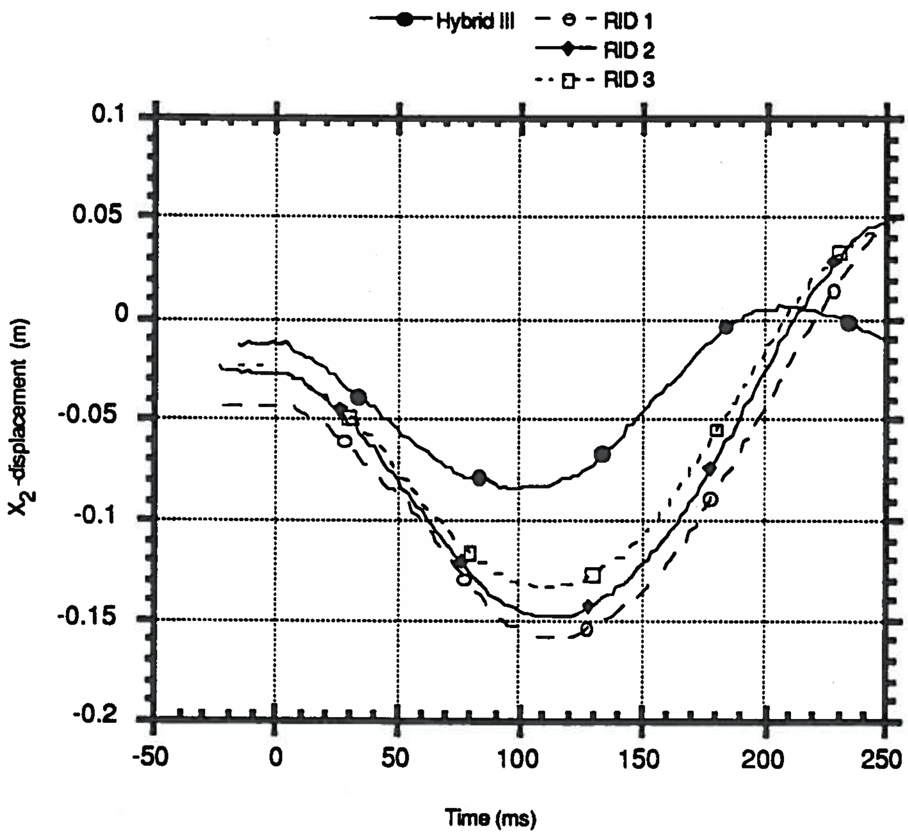

Figure 8: Displacement of the head-CG in X_2-direction.

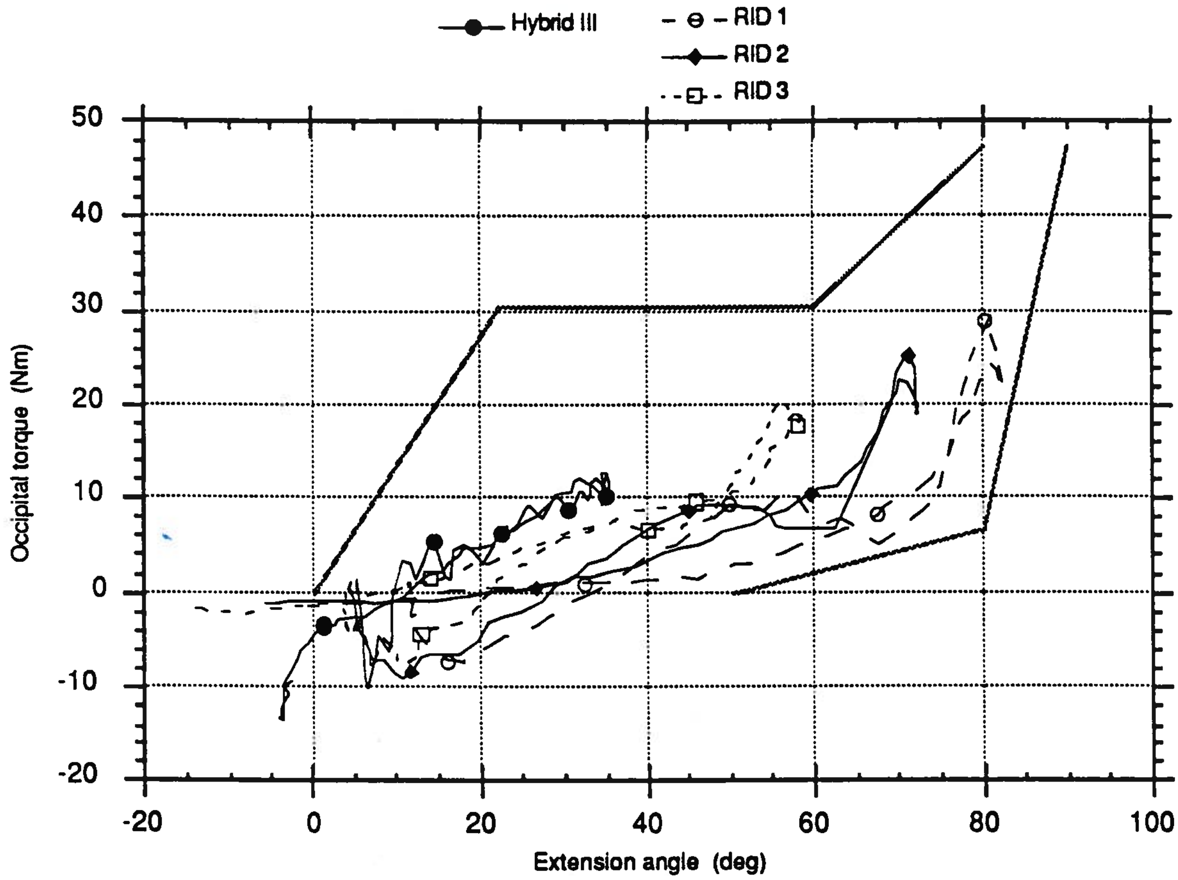

Figure 9: Examples of occipital torque as a function of extension angle compaired with the head-neck response-corridor for neck extension, proposed by Mertz and Patrick(1971). According to the sign convention, positive torque counteracts extension. An extension angle of 0° corresponds to the neck-posture of a person seated in a car-seat with 15° rearward seat-back angle.

The torque response at the lower neck was almost identical for the three RID-configurations with peak values of 60-65 Nm and the peak value for the Hybrid III-neck was 55 Nm.

The maximum X_3-accelerations of the head increase with decreased neck stiffness (Table 3).

Table 3: Maximum X_3-accelerations of the head.

Neck	RID 1	RID 2	RID 3	Hybrid III
Acc. (g) -	8.1	6.9	6.5	5.1

DISCUSSION

The chosen ranges of angular movement of the RID-neck were based on data from Kapandji (1974) and from White and Panjabi (1978). For the cervical spine, a typical range of voluntary motion was reported to be 40° in flexion and 75° in extension for a young adult subject (0° represents a normal standing posture). In the RID-neck, this range was increased with 5° in booth flexion and extension to allow for some hyper-extension and -flexion. It was considered to be an advantage if the neck does not bottom out at the limit for physiological range of motion. Bottoming-out will obstruct quantitative measurement of the hyper-extension.

A number of studies to determine the range of motion of the cervical spine have been published and the results differ to some extent. In a literature review, States et al. (1972) found ranges of motion for extension of 61°-93° and for flexion of 54°-67°. Wismans et al. (1987) observed maximum flexion angles of more than 100° in severe frontal impacts with volunteers. These findings imply that the range of motion in flexion of the RID-neck perhaps ought to be wider. But since the RID-neck is ment for studying the rearward phase of the neck motion in rear-end collisions of low severety the flexion range is of minor interest (except for the maximum allowable rearward horizontal translational displacement of the head relative to the torso). Foust et al. (1973) reported total average ranges of motion for different age-groups and sexes of 94°-138°. Generally, the range of motion decreases with age and women have a wider range than men (Foust et al., 1973).

For simplicity, all the vertebra of the RID-neck were given the same height i.e. 16mm. Each vertebra could have been given an individual size but this would give a higher degree of refinement than what was motivated by the scarce amount of volunteer data that was available. In this study, the stiffness was chosen to be constant along the whole neck in all the tests. It would, however, be possible to insert foam elements of different stiffnesses at different levels of the neck to further modify the neck properties. The angular displacement between two adjacent vertebrae as a function of applied torque can be modified by changing shape, size and foam-type of the foam-blocks. The damping characteristics could also be altered by changing the foam-type.

Only a few tests with volunteers in staged rear-end collisions have been published, for example; Severy et al. (1955), Mertz and Patrick (1967), Tarriere and Sapin (1969). The results by Tarriere and Sapin were found to be the most suitable for validating the RID-neck. It was possible to reproduce these tests by means of a Hybrid III calibration-pendulum with reasonable accuracy. The tests presented by Tarriere and Sapin were done on subjects that were distracted in order to minimise the anticipation of the impact. This no doubt, best resembles the situation in a rear-end collision. The standing volunteers were impacted, at shoulder level, from behind by a heavy pendulum. The mean acceleration at shoulder level was 2-3g with 120ms duration The volunteers thus experienced a velocity change of roughly 10km/h (6mph) which is relevant for most whiplash injuries.

The volunteers held their heads in a position with some rearward angular displacement at the moment of impact (Figure 5). This posture is presumably achieved by extension of the upper joints of the cervical spine. During a whiplash-motion, with 0° initial head-angle, the same rearward angular displacement would have corresponded to a very different posture of the cervical spine with extension of the lower cervical joints and some flexion of the upper cervical joints. We assume that the initial rearward head angular-displacement of the volunteers had a limited influence on the maximum extension-angle.

Figure 5 is a comparison between the RID- and Hybrid III-results, and the volunteer results. The "RID 3" fits closest to the volunteer results. Even though the volunteers were distracted, they were probably aware, to some extent, of the coming impact and this might have helped them to resist the head motion. Usually, only strong and healthy subjects are accepted as volunteers in this type of experiment and they are not representative for the whole adult population. If an older and less athletic subject was exposed to the same impact as in the volunteer tests, the maximum angular displacement of the head could have been greater. A dummy-neck for rear-impact testing should be representative for the whole population of car occupants and should, therefore, at least not be stiffer than the "RID 3" in the extension-mode, which is the case for the Hybrid III-neck.

In Figure 9, the corridor for torque-extension neck-response by Mertz and Patrick (1971) is shown together with the corresonding results from the pendulum tests. The corridor is too wide to provide any guidace in this work. The corridor was proposed together with some other performance requirements for dummy-necks. The requirements were further developed by Mertz et al. (1973) and provided the basis for the development of the Hybrid III-neck (Foster et al., 1977). The requirements by Mertz et al. (1973) where meant for much higher impact velocities than what we are interested in and are based on test-data from a volunteer with pre-tensed muscles so they are not applicable for our purposes.

The largest deviation between the RID- and the volunteer-results is the deceleration of the forward head-neck motion of the volunteers, starting about 150 ms after the impact (Figure 5). Apparently, the extensor muscles actively brake the forward motion. The braking function of the extensor muscles cannot be simulated with any of the dummy-necks tested. The Hybrid III-neck shows a deceleration of the forward motion, similar to that of the volunteers, but not until the neck passes 0° and goes into flexion where it is much stiffer (Deng, 1989). The RID-neck is not much stiffer in flexion than in extension in order to give low resistance to horizontal translational displacement between head and torso. No efforts have been made to give the RID-neck good bio-fidelity in flexion mode. It was assumed that the typical whiplash injuries occur during the extension-part of the whiplash-motion and thus that the dummy-neck must primarily have good bio-fidelity at the initial part of the motion. The largest neck-loads are likely to occur between 0 ms and the time for maximum forward angular velocity of the head, about 160 ms later.

The trajectory (Z_2-displcement as a function of X_2-displacement) of the head-CG is almost identical for the Hybrid III and the three different RID configurations. Melvin et al. (1972) emphasised the importance of the head trajectory for dummy-necks. Unfortunately no data have been found on the head-trajectory during whiplash-motion to validate the RID-neck with.

The angular motion of the head is delayed about 20 ms for the three RID-neck configurations but not for the Hybrid III-neck (Figure 5). The X_2-displacement, however, starts almost simultaneously for all the necks (Figure 8). This shows that an initial horizontal translational-motion of the head relative to the torso takes place with the three RID-necks. Unfortunately no published data from rear-impact tests with human volunteers or cadavers have been found where a corresponding comparison can be made. Wismans et al. (1987) observed the corresponding translational-motion of the head in frontal impact. Since this type of translational-motion is possible during voluntary motion, both rearward and forward, it is most likely to occur also during reaward whiplash-motion.

The deviation between the original extension-angle curves and the 9th degree polynomial curve-fits were low exept for times less than about 20 ms after impact. Thus, the calculated angular velocities and angular accelerations are less reliable in this interval.

The direction of the inertial loading of the head and neck differs between the volunteer tests and the pendulum tests. The first discrepancy is the opposite sign of the gravity and the second is the 14° forward angular displacement of the lower neck in the pendulum tests (Figure 4). This results in a decrease of the violence to the neck, corresponding to a decrease of the pre-impact velocity of about 1% for the Hybrid III neck and 5% for the "RID 3" neck. This discrepancy is small, considering the greater uncertainty of the acceleration at shoulder level for the volunteers (2-3 g).

The pendulum arrangement did not allow complete control of the initial position of the head and neck and certain displacement occurred (Figures 5 and 8). For the RID-neck, the occipital-torque increases progressively with increased angular displacement under static conditions. The same is true for the Hybrid III-neck (Deng, 1989). A small displacement of the head at the start of the impact will only have a minor influence on the maximum displacement.

The tests had good repeatability. Each neck configuration was tested three times and for identical tests the difference of the time integrals from 0 ms to 120 ms for X_3-head acceleration, occipital torque and occipital X_3-force was generally <5%.

CONCLUSIONS

* A new neck for rear-end collision testing at low impact-velocities has been developed. It consists of seven cervical and two thoracic vertebrae connected with pin-joints, thus, allowing motion in the sagittal plane only. The neck is designed to fit the Hybrid III-dummy.

It has a range of motion of 83° in extension and 48° in flexion and it is pre-flexed 15° in sitting position.

* The results of the volunteer tests by Tarriere and Sapin (1969) were found to be the best available for validating a dummy-neck for rear-end collision testing at low impact-velocities (<20 km/h) even though the conditions under which the tests were undertaken lacked some preciseness.

* It was possible to adjust the response of the RID-neck to give satisfactory accordance with the volunteer results of Tarriere and Sapin (1969). The Hybrid III-neck proved to be too stiff under the given conditions.

* If new neck-response data become available, the stiffness- and damping-characteristics of the RID-neck can be further adjusted to better fit these data. The neck could also be redesigned with a lordosis in standing posture and with muscle substitutes connecting directly between the head and torso.

* Preliminary low-speed rear-end collision sled-tests have shown that the RID-neck functions well together with the Hybrid III-dummy. With this modified Hybrid III-dummy, it appears to be possible to study the influence of different production-car seats and head-rests on the head-neck kinematics.

ACKNOWLEDGEMENTS

This study was supported by the Swedish Transport Research Board (TFB). The manufacturing and the testing of the RID-neck were done at the test-facilities of Electrolux Autoliv in Sweden. We wish to thank Professor Bertil Aldman, former head of the Department of Injury Prevention, for most valuable advice and constructive criticism; Mr. Yngve Håland, Manager R&D, Electrolux Autoliv, for putting the test-facilities at our disposal, free of charge; Mr. Lennart Thorngren, Senior Research Engineer, Department of Injury Prevention, for valuable ideas and help.

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