NECK INJURY PREVENTION IN REAR-IMPACT CRASHES

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ABSTRACT

Although much progress has been made in the field of passive car safety in the last years, there is still a strong need for safety improvements in rear-end impacts. While rear-end collisions seldom cause fatal injuries, lesions of the cervical spine are known to cause a high societal cost associated with their often long-term consequences.

The critical body region in rear impact cases is the cervical column. The biomechanics are not yet understood sufficiently to define tolerance limits for soft tissue injuries that could be used for the design of restraint systems. Nevertheless, evidence is high that lesions of the cervical column are caused mostly by shear forces during the first phase of the impact. Therefore, the best strategy to reduce the risk of injury is to control the kinematics of the head-neck-thorax system during impact in such a way that relative displacements within this system are minimised.

A concept for a car seat offering enhanced safety has been developed and test models have been built. Although this seat has been designed for the harder conditions in low mass vehicle collisions, the concept can easily be adapted to conventional cars. The seat features an automatically controlled head restraint adjustment mechanism which guarantees a small and relatively well defined distance between the occupant's head and the head restraint. Based on computer simulations, paddings for the different regions of the seat back and an energy absorbing yielding mechanism of the seat back have been designed in a way that only little relative displacements in the head-neck-thorax system are to be expected even during a severe rear-end impact. Different occupant sizes ranging from the 5th percentile female to the 95th percentile male have been considered.

A series of rear impact sled tests with velocity changes from 12.2 to 38.6 km/h and acceleration levels from 6 to 30 g has been performed using a 50 percentile Hybrid III dummy equipped with the new TRID neck. The

measurements show a good correlation with the simulation and the risk of cervical column injuries is considered to be substantially lower than in conventional seats.

A SAFE SEAT FOR LOW MASS VEHICLES

The Working Group on Accident Mechanics has developed a low mass vehicle (LMV) with a curb weight of 650 kg, called "Cratch". This experimental vehicle demonstrates that a high level of passive safety for the occupants of low mass vehicles is achievable in frontal collisions (Frei 97). The development of a car seat suited for use in LMVs has been a part of this project. The seat is an important element of the restraint system: In the case of a frontal crash, the initial position of the occupant is defined by the contour and position of the seat, and, during the crash, a part of the occupant's kinetic energy is absorbed through deformation of the seat base. In rear-end impacts the seat represents the entire restraint system.

During a collision against a conventional car, the low mass vehicle, due to the fundamental laws of motion, is exposed to higher accelerations and a larger change in velocity than its counterpart (Niederer 93). The seat presented here was specially adapted to these severe conditions. Nevertheless, almost every feature of the concept could easily be adapted for use in conventional cars. The main focus of the development was on the improvement of the rear-end impact safety, which represents a substantial problem, also for conventional cars.

Compared to the considerable improvements of crash safety in frontal and side impacts accomplished during the last years, progress concerning the rear-end impact safety has somewhat stagnated. This may be related to the fact that rear-end crashes are often considered to be less dangerous, since there is a very high surviving probability for the occupants. In spite of this, it is very worthwhile to invest in rear-end impact safety since injuries caused by this collision type do not only cause high amounts of compensation costs but also can have very unpleasant consequences to the occupants involved.

THE ADJUSTMENT CONCEPT

In order to provide an adequate safety level and an ergonomically correct driving environment to occupants of a wide range of size and weight, a seat needs various adjustment capacities. The seat must be adjustable in the longitudinal axis. The seat base should be adjustable in height and angle. The horizontal distance between backrest and front edge of the seat base (seat base length) should be variable in order to achieve a sufficient support for the thighs. Correct horizontal and vertical adjustment of the head restraint is indispensable for an efficient injury prevention in rear-end impacts.

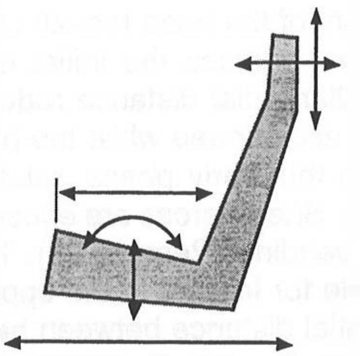

Figure 1: Adjustment parameters of the seat.There is no seat back recliner adjustment. This is not considered necessary in combination with the other adjustment parameters and the interior geometry of the Cratch vehicle.

The problem with such adjustment possibilities is that they only make sense if they are applied correctly by the occupants. It has been shown (Parkin 93) that, especially in the case of head restraint adjustment, this cannot be taken for granted. Therefore, in the seat presented here, occupants are only given control over one single parameter: the position of the seat on the longitudinal axis. All other adjustments are performed automatically. The adjustment of the seat base and a part of the vertical adjustment of the head restraint are mechanically linked to the horizontal movement of the seat in such a way that suitable seating positions result for all person sizes ranging from the 5th percentile female to 95th percentile male.

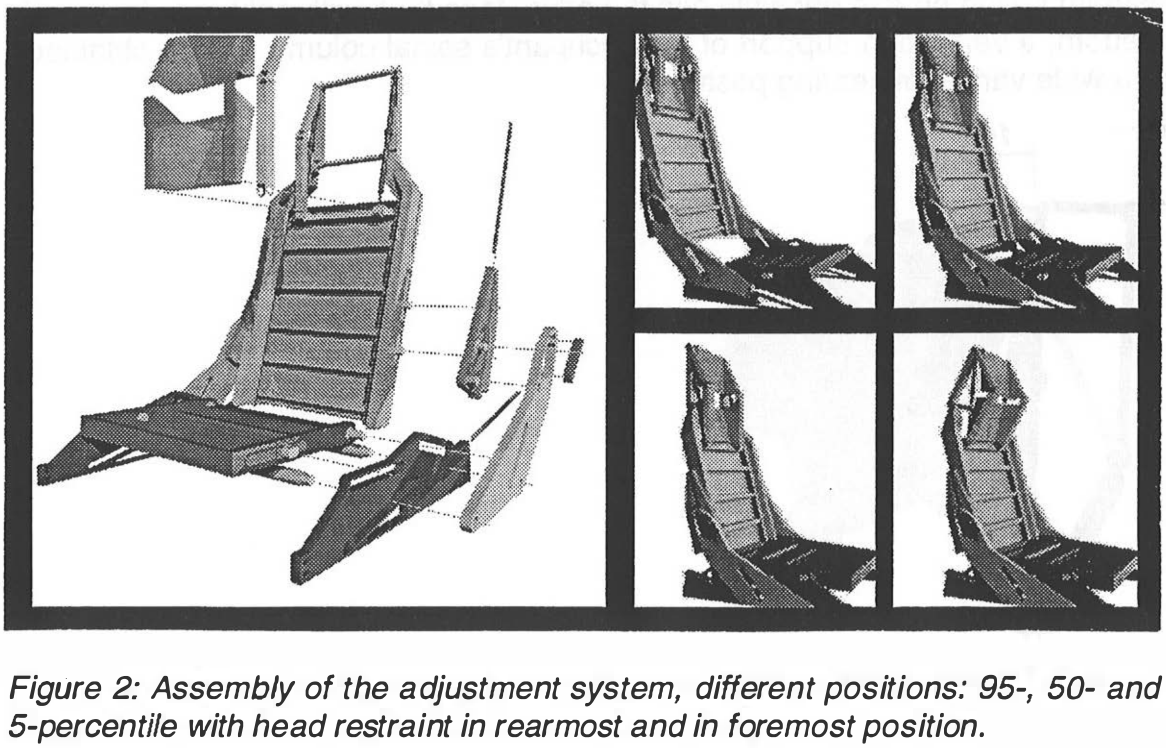

Figure 2: Assembly of the adjustment system, different positions: 95-, 50- and 5-percentile with head restraint in rearmost and in foremost position.

The horizontal and the final vertical adjustment of the head restraint are controlled electronically. The horizontal adjustment reduces the initial head-to-headrest distance in a rear-end impact. A smaller initial distance reduces the time during which the thorax of the occupant is accelerated while the head still remains more or less in its original position. In this early phase, relative displacement between head and thorax takes place. Shear forces are effective and the cervical column is forced into a S-shaped bending (Penning 92). There is evidence that these shear forces are responsible for lesions in the upper neck region (Walz 95). Beside the reduction of the initial distance between head and head support, an automatic horizontal head restraint adjustment has the advantage that it can be used to obtain a comparatively well defined initial distance (Muser 94). This helps to implement additional measures to reduce the horizontal displacement of the head relative to the torso during rear-end impact.

An automatic vertical adjustment is necessary for two reasons: first, it guarantees that the head is sufficiently supported and hyperextension is prevented, and second, an exact vertical adjustment is required to enable the horizontal adaptation process and a continuous support of the head-neck contour of the occupant. The seat back and the neck-head support are designed as a single unit. Therefore, vertical adjustment of the head restraint requires translation of the whole seat back. Since the shoulder belt passes through a diversion clamp in the seat back, this leads to an automatic adjustment of the belt geometry as well.

The geometry of the horizontal adjustment mechanism is based on a parallelogram, with the head restraint performing a translational movement and the neck restraint rotating with its lower end fixed on the seat back. A head-neck restraint based on this principle has the advantage that, with only one degree of freedom, a very good support of the occupant's spinal column can be obtained for a wide variety of seating postures.

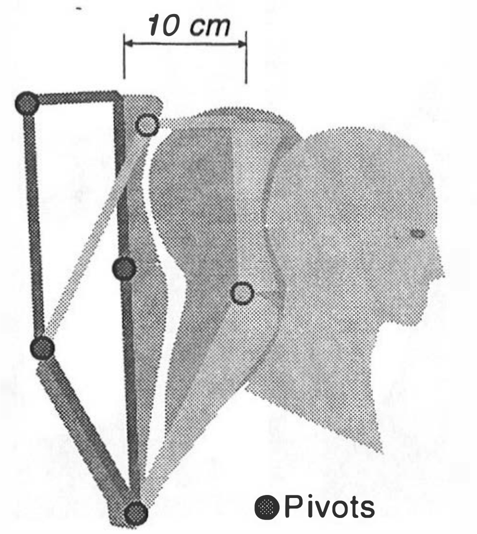

Figure 3: The mechanism of the horizontal head-neck support adjustment

The mechanism is driven by two spindles positioned in the longer diagonals on each side of the construction. The spindles are powered by an electric motor through flexible shafts. This makes it possible to place the motor virtually anywhere in the vehicle, so that disturbance of the occupant caused by motor and gear noise can be minimised. A capacitive sensor in the headrest measures the distance to the back side of the skull, and an electronic controller maintains a constant distance of approximately 35 mm. The adjustment range is about 100 mm. If the occupant chooses to lean his head on the head restraint, this is possible if the mechanism is in its rearmost position. If the sensor does not detect any object in front of the head restraint, the system will stop instead of moving to the foremost position. Thereby, unnecessary movement of the headrest is prevented, such as in case where the occupant temporarily moves to the side so that his head is outside of the space in front of the head restraint. Due to the high time constant of the controller system, the head-neck support represents a passive restraint during a collision.

A functional mock-up of the seat has been built. The adjustable geometry and the automatic controller system have been successfully tested in this mock-up.

ENERGY ABSORPTION

In addition to the functional mock-up, two crash-testable models of the seat have been built. They were used in the Cratch experimental low mass vehicle in a full scale frontal crash test with a delta-v of more than 70 km/h, and in a series of sled based rear impact tests.

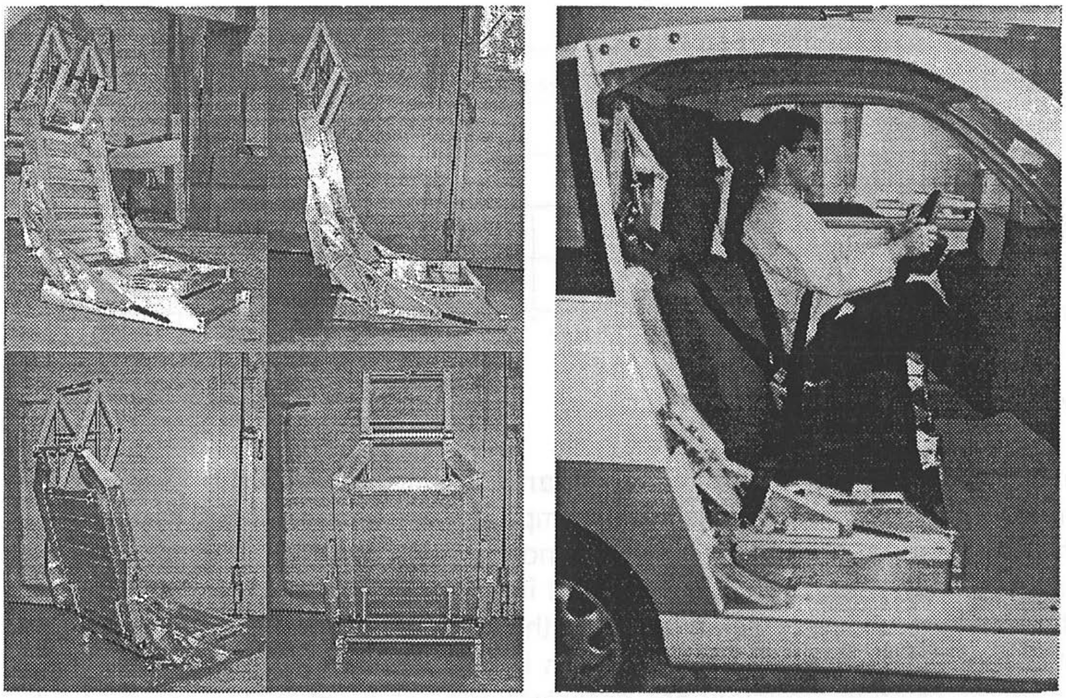

Figure 4: The crash test model of the seat: raw structure and completed seats integrated into Cratch low mass vehicle. Seating position is more upright as in conventional cars.

The requirement for a geometrical adaptability for the spectrum ranging from the 5th to 95th percentile occupant alone is not sufficient; the energy absorption capabilities of the seat must also be made suitable for the whole group. This means that the seat must deform softly enough not to exceed tolerance limits for light persons but must also provide enough deformation space for heavy occupants. Since the amount of prototypes was limited, e.g. more than one test per seat specimen had to be performed, the seats had to be reusable, leading to a rather robust and heavy construction. Seats for 'real world' use do not have to fulfil the reusability requirement, allowing for a less heavy construction.

The seat has been designed to withstand an sled impact speed of 33.3 km/h. This corresponds to a situation in which a standing low mass vehicle is hit on the rear end by a conventional car of twice the weight travelling at 50 km/h. Based on a force-deformation curve of an existing car and an assumed characteristic for the Cratch (which has not been rear-end impact tested) an acceleration-time curve for the Cratch has been calculated and simplified for use in simulations and sled testing. The maximum acceleration level is 30 g. Since it is known that cervical spine injuries can already occur at much lower loads, impact speeds of 22.2 and 11.1 km/h have also been taken into account for the design of the seat. The corresponding acceleration levels for these speeds are only 20 and 12 g, because in these cases impact energy is considerably smaller and the deformation zones of the cars are not deformed to a degree that higher forces (leading to higher accelerations) are built up.

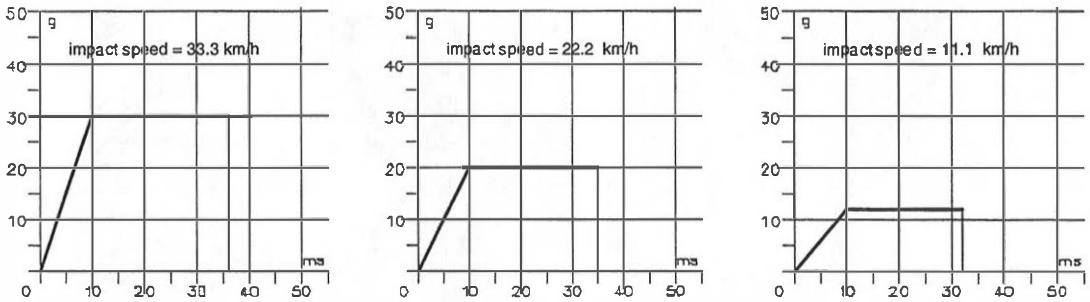

Figure 5: Acceleration pulses

In order to find suitable stiffness characteristics for the different energy absorbing units of the seat, a simple computer simulation model was used in which the occupant is modelled by four independent masses. Realistic results with such a model can only be expected in case where there are no, or very little translational displacements between the body parts. For our purposes, this is not a real disadvantage, since the aim is to find a setting wich results in a minimum of relative translational deformations (at least in the upper body regions). In a first step, the model was verified through comparison with a well-tried rigid body simulation program. Unfortunately, there is no model of the cervical spine available yet that is able to exactly mimic the behaviour of a human neck.

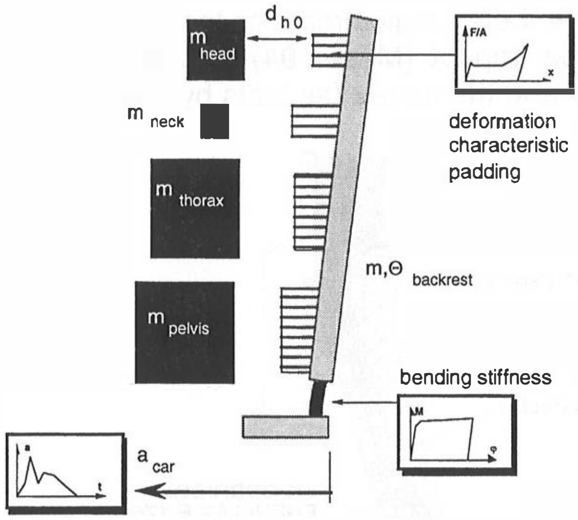

Figure 6: Simplified rear-end impact model of occupant and seat, used for computer simulation. The deformation characteristics of the paddings have been evaluated by dynamic impact pendulum tests.

Energy absorption is performed both by foam paddings and by rotational yielding of the seat back. Yielding is controlled by a deformation element, which consists of a three point bending beam made of aluminium. The yielding moment is 3000 Nm. During loading, the element builds up deformation force in the elastic range only gradually. This is undesirable as it causes a faster backward movement of the head restraint in the first phase of the collision. Bolts have therefore been integrated in the construction to obtain a deformation characteristic that sooner reaches its energy absorbing level. The bolts shear off during the onset of the yielding process and cause higher forces at the beginning of the deformation process.

The replaceable deformation elements are the only structural parts of the seat that are supposed to absorb energy. Energy absorbing properties of other load bearing components are irrelevant. This means that the seat concept and the choice of material for the realisation are almost independent of each other.

The centre of rotation of the yielding back rest is positioned relatively high above the seating level. Yielding of the back rest is thus delayed and an earlier contact between head and head restraint is obtained. Because the pelvis is already in contact to the back rest at the beginning of the crash, no considerable relative velocities between the pelvis and the back rest arise during impact and therefore little deformation space is needed in this region.

The acceleration levels of the different body parts are mainly influenced by the stiffness characteristics of the foam paddings. The paddings have to be chosen such that relative movements between head, neck and thorax are minimised. A combination was found that works adequately under the conditions mentioned above.

Even with an automatically adjusted head restraint, for comfort reasons there will remain some initial distance between the head and the head restraint, causing a delay of the acceleration of the head in comparison to the thorax. A layer of a very soft foam applied in the thorax region reduces the acceleration of the thorax in this first phase of the impact (Muser 94) and thus helps to synchronise movements of the head and the thorax (as tests by Svensson (96) have shown).

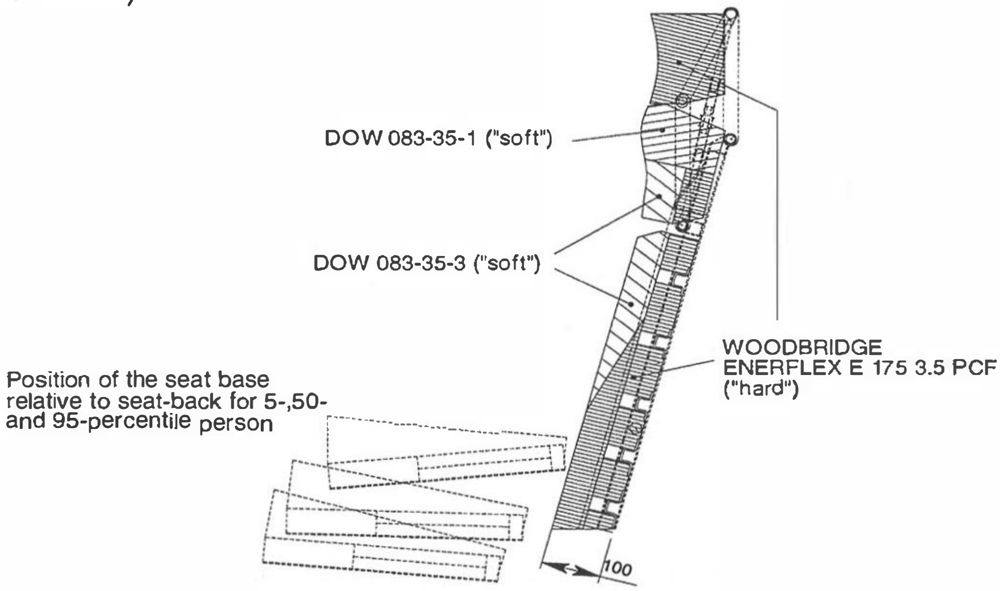

Figure 7: Assembly of energy absorbing foams in the seat back. A hard foam type (Woodbridge Enerflex) and two softer foams (Dow) have been used. Empty spaces in front of protruding structural components prevent excessive compression of foams and increase of forces in these regions.

SLED TESTS

A series of six rear impact sled tests has been performed. A Hybrid III dummy equipped with a TRID neck (an improved version of the RID neck (Svensson 92), developed by TNO) has been used in all tests. Comparative tests have shown that the RID neck reproduces the behaviour of a human neck under rear-end impact conditions much better than the standard Hybrid III neck (Geigl 94). The neck is only available in a 50th percentile version. Therefore, all tests have been carried out with a 50th percentile dummy only, even though other occupant sizes had been taken into account during the design process of the seat. The main interest of the tests was focused on the relative movement in the neck region. A high speed video system plus two high speed 16 mm film cameras have been used for the kinematic analysis.

The dummy was set into an appropriate seating position and subsequently the distance between back of the skull and head restraint surface was adjusted to 35 mm. The automatic adjustment system was not integrated since it is not necessary for dummy tests.

The first test was performed at an impact speed of 11.1 km/h. Due to elastic rebound in the sled braking system (sheet metal brakes) the total change of velocity was 15.2 km/h. There was practically no observable S-shape deformation in the TRID neck.

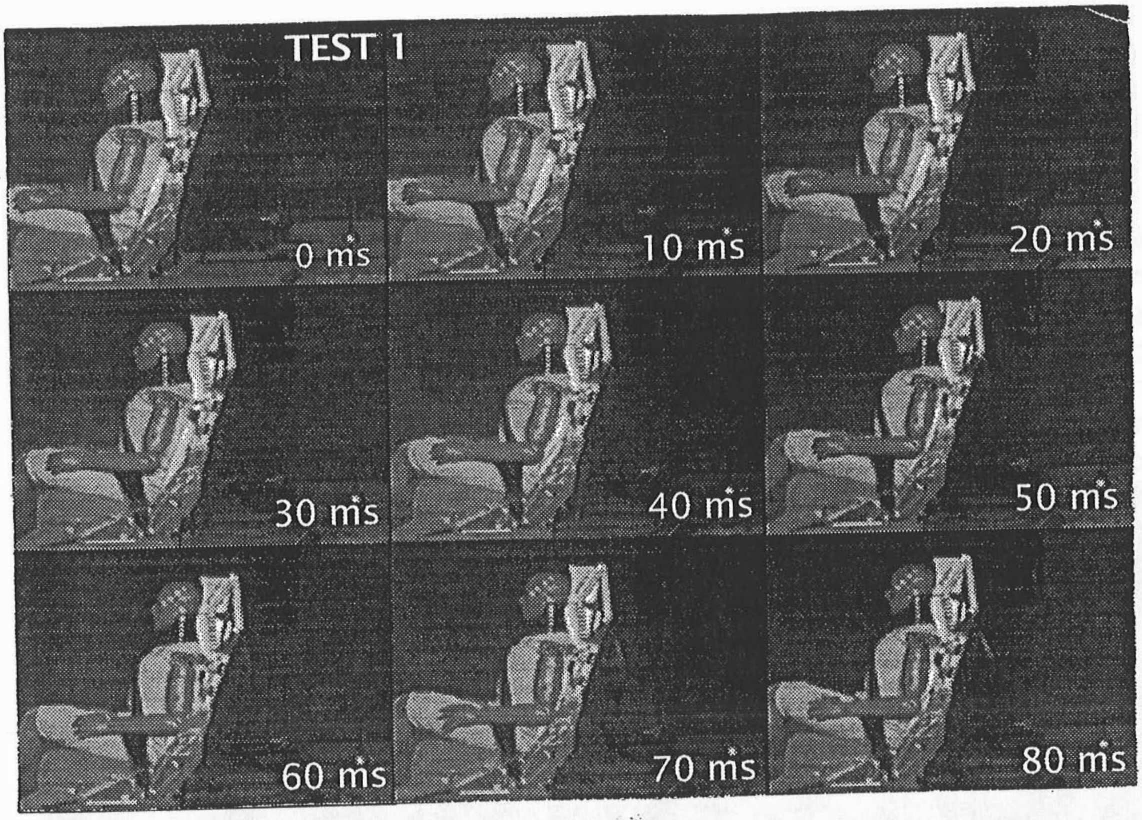

Figure 8: No S-shape bending in the neck is visible during the delta v=15.2km/h impact

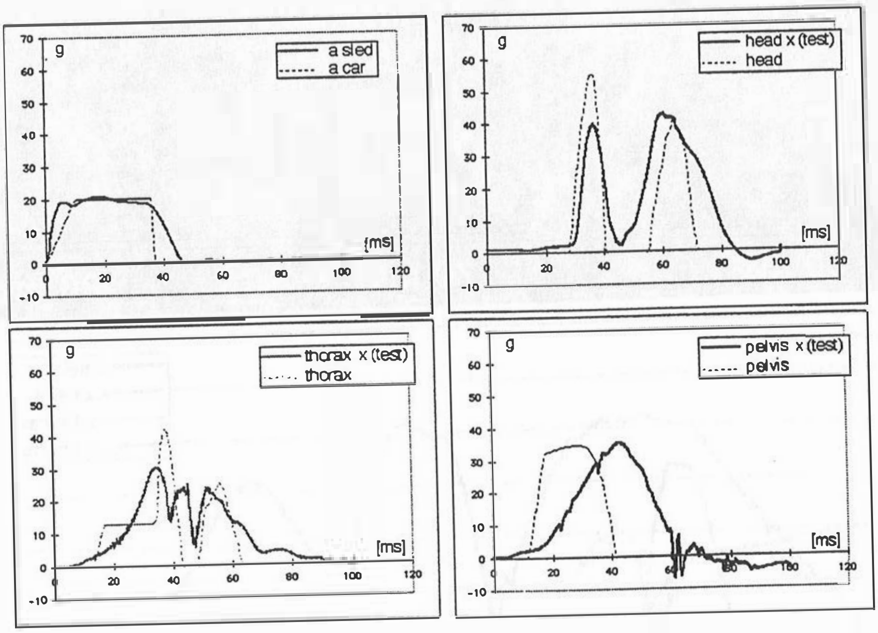

Figure 9: Comparison of acceleration data obtained by computer simulation (thin curves) and measurement (thick curves) from test #2

The second test was carried out at an impact speed of 22.2 km/h (delta v=26.3 km/h). During the first phase, the behaviour of the dummy was similar as observed in the first test: the thorax intrudes into the padding, travelling together with head and neck like one rigid unit until the head comes in contact with the head restraint. The neck never touches the neck support, because the TRID neck differs in contour from a human neck. In a second phase, the head loses contact with the yielding head support and some small S-shaped deformation in the neck can be observed. Afterwards the head contacts the head restraint for a second time. Elastic bending of the head-neck support can be observed, and a relatively high amount of elastic rebound energy (42% of the head's impact energy, calculation based on acceleration data) can be determined for the head, but this does not seem to have a negative effect on the kinematics.

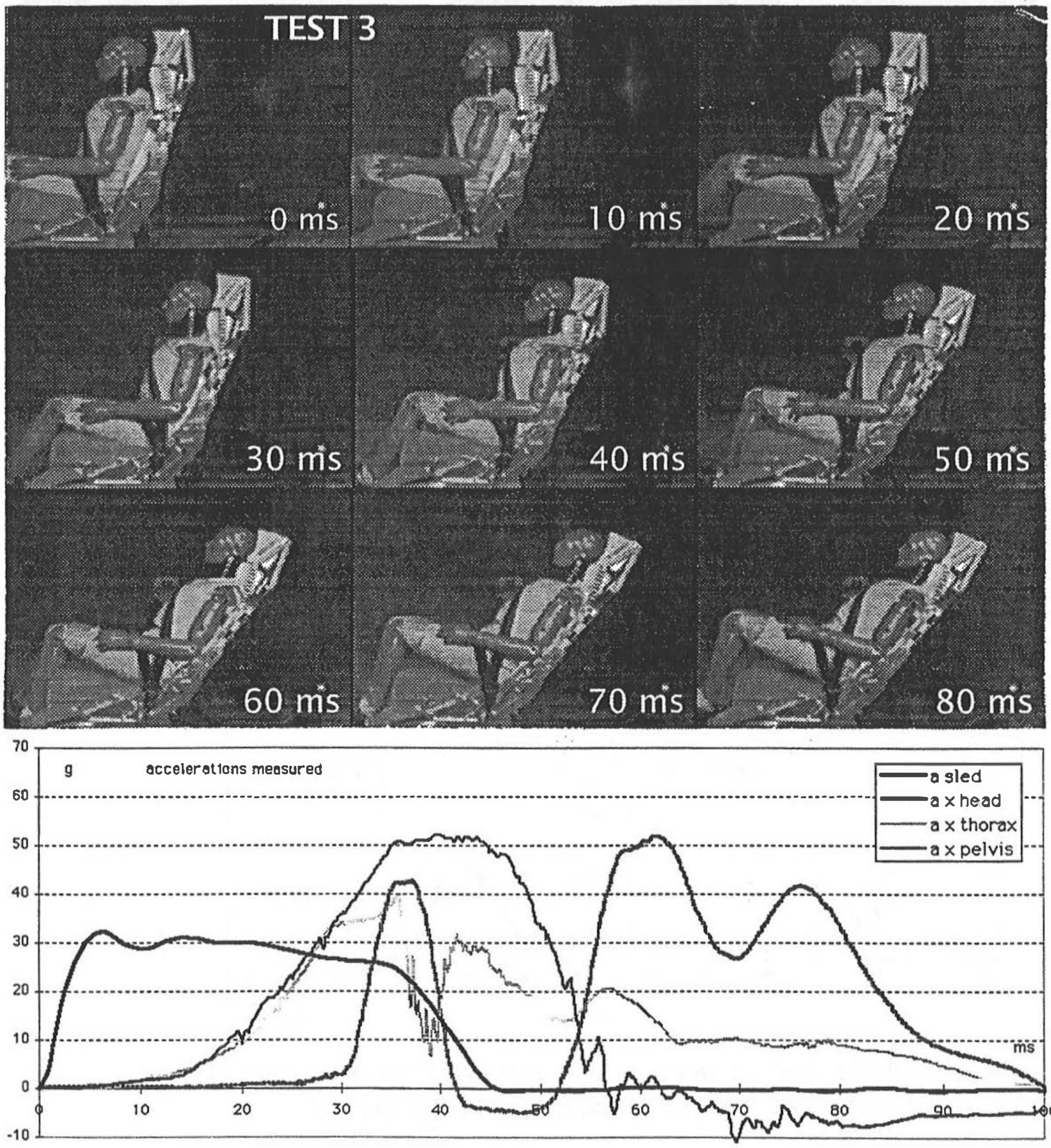

Figure 10: dummy motion and accelerations from test #3 (delta v=38.6 km/h)

The third test was performed at an impact speed of 33.3 km/h (delta v=38.6 km/h). The back rest did not collapse but significant yielding appeared. The yielding angle of 26° was higher than predicted by the computer simulation (22°), but there was still energy absorbing potential left in the deformation elements (needed for heavier persons). A part of the yielding resulted from plastic deformation in the base structure of the seat. This was not intended but did not have a negative effect on the test results. Because of this damage the second specimen of the seat was used for the remaining tests. The behaviour of head and neck was similar as observed in the second test. In the last phase of the impact, flexion of the neck becomes visible. At this time, the pelvis is already travelling away from the seat back and, as it forms an almost rigid unit together with the thorax (much more than this would be true for a real human), rotation of the torso occurs which forces the neck into flexion. However, this flexion does not represent any danger. Elastic rebound of the head (15% of impact energy) was much smaller than in the second test.

The fourth test corresponds to the first one, with the only difference that the mean acceleration level was reduced by 50%. This simulates the conditions in a standing car struck in the rear end by a car of the same weight travelling at 22 km/h. Like in the first test, there was virtually no visible relative movement in the neck region.

The fifth and the sixth test correspond to the second and the first test, with the difference that softer paddings have been used in both the thorax and the head region. The aim was to reduce the 'double impact' effect of the head, which indeed was accomplished. On the other hand, the head padding was now too soft, causing delayed deceleration of the head and leading to a less favourable neck deformation pattern.

In all tests pelvis acceleration started later than predicted by the computer simulation. This effect can be explained by the fact that in the computer model the surface area between the body and the padding was assumed to be flat. However, the body surface of the dummy is bent, e.g. the contact area and therefore also the contact force is a function of the intrusion into the padding. This effect had been considered for the head (which was modelled as a sphere) and the neck (cylinder). The spherical shape of the head is problematic in that the onset of considerable acceleration of the head is delayed until the head has intruded sufficiently into the padding. A layer of hard material on the head restraint surface would conceivably improve these force-deformation characteristics.

In none of the tests existing tolerance limits of head, thorax or pelvis accelerations have been exceeded. Moments and forces in the neck have been measured but, as there are no applicable tolerance limits for the neck (let alone for tests performed with the new TRID neck), it is impossible to make a precise biomechanical statement with regard to these quantities.

CONCLUSION

Even if, due to the lack of biomechanical tolerance criteria, the achieved safety improvements cannot be quantified, the analysis of the kinematics show that a considerable decrease of neck injury risk is possible with the energy absorbing components and the geometrical adjustment concept presented here. Due to an almost complete lack of relative movement within the head-neck-upper thorax region, injury risk during low speed impacts, which today are responsible for a large percentage of neck injuries, is considered to be very low.

It seems very probable that even better results could be obtained with a back rest that does absorb energy through translation instead of rotation, although such a system might be more difficult to implement and might cause other problems such as injuries to legs and feet of occupants in the rear seats.

The simulation model used in the design process delivers results of sufficient precision and, in combination with more sled tests, would lend itself for a further optimisation of foam and seat back properties.

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