

Design concepts for an integrated whiplash mitigating head restraint and seat

M. Acar and S.R. Bewsher

Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Loughborough, UK

ABSTRACT

This paper presents design of a concept for an integrated head restraint and car seat system to mitigate whiplash in rear-end vehicle collisions. The main emphasis is on a concept, which combines a reactive head restraint with a reactive seat. The chosen concept is developed in the form of mechanical linkages using linkage analysis software, SAM 6.1. A human model positioned in a 'good' driving posture is used to show how the head restraint and seat would operate using a typical crash pulse used for dynamic sled testing of automotive seats. The head restraint system is capable of translating into an optimal position of 40 mm forwards and 60 mm upwards in 12 ms, before whiplash-induced injuries start to take place. The reactive seat is also capable of reclining 15 degrees. The combination of reducing the backset and reclining the seat to reduce the relative motion between the head and torso has the potential to reduce the whiplash-effect-related injuries in rear-end collisions.

1. Introduction

Whiplash is a disorder of soft tissues of the neck from a sudden differential movement between the head and torso, straining the muscles and ligaments of the neck beyond their normal range of motion, most often occurs as a result of motor vehicle collisions [10]. Whiplash injuries can result from impacts in all directions; however, it most often occurs from rear impacts in car accidents at low velocity changes, typically less than 25 km/h [4,13]. In a rear impact, the head and torso of an occupant move backwards relative to the seat (vehicle). The torso is supported by the seat back, hence it will have a limited motion due to deformation of the seat padding and frame. The occupant body may also ramp up the seat as the seat back deforms backwards under the effect of the impact from the torso. The head sharply rotates backwards until it is stopped by a head restraint. Finally, the head rotates forward and the torso rebounds (Figure 1). All this happens typically within 125 ms causing a whiplash disorder in the occupant's cervical spine. Analyses of high speed films have revealed a distinctive kinematic response of the cervical spine to whiplash trauma [7]. Figure 2 shows, within the 50 to 70 ms time period, the initial phase of a developing S-shaped curve in the cervical spine with extension at the spine's lower levels and flexion at upper levels. The 100 to 125 ms time period represents the final phase with extension of the entire cervical spine.

Although it is officially classed as a minor injury, whiplash has the potential to lead to many long lasting and uncomfortable symptoms. It is estimated that within the European Union that 800,000 citizens suffer from whiplash every year [14], with 40,000 resulting in long-term suffering and a socio-economic impact of approximately 10 billion euros annually.

Whiplash injuries include muscle and ligamentous strain producing transient cervical pain, symptoms of headache and concussion, and injury to the intervertebral disks infrequently requiring cervical fusion [18]. The Quebec Task Force created a system whereby whiplash-associated disorder was split into following four categories of severity [19]:

- Grade 1: no sign of physical damage to the neck or upper back.
- Grade 2: signs of damage to the neck or upper back, i.e. decreased range of motion and point tenderness.
- Grade 3: neurological damage to the neck or upper back, i.e. decreased reflexes, sensation and strength.
- Grade 4: fracture or dislocation of the neck and upper back.

The main feature of a car seat that prevents whiplash is the head restraint. One, which is designed for the right geometry and aligned correctly, will vastly reduce the incidence and risk of injury to the head, spine and neck during a collision, especially for

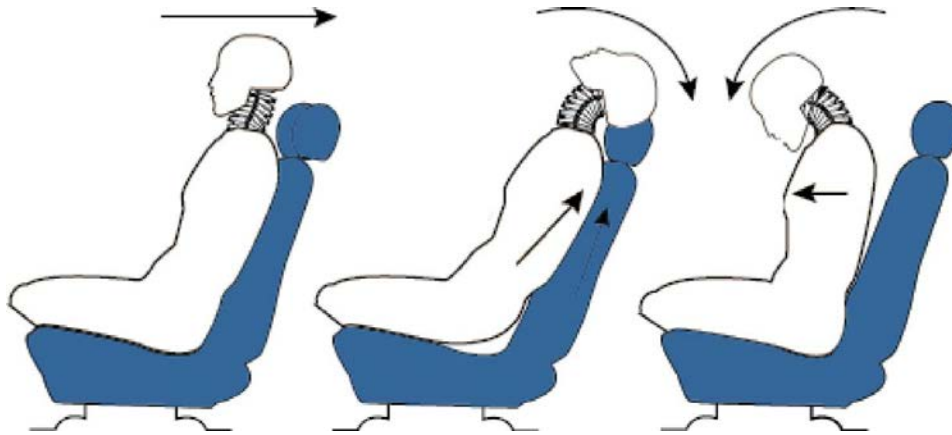


Figure 1. Whiplash injury most commonly occurs during rear-end car collisions from motion of the spine and neck [17].

females who are more susceptible to whiplash injuries than men [6]. It was shown through simulation using a MADYMO head-- neck model that whiplash injuries can be reduced by limiting the head restraint backset (Figure 3) to values less than 60 mm [20]. The occupant's seating posture, position and angle of the head are also important to benefit from an improved seat design [12].

This paper reports the design and development of an effective concept which combines a reactive head restraint system with a reactive seat system for a more effective whiplash mitigation. The head restraint system adjusts itself during a rear-end collision impact to an elevated position and closer to the occupant's head reducing the backset. The reactive seat system is capable of rotating rearwards in a controlled manner to reduce the differential motion between the head and torso. Integrating the two systems into one has the potential of further reducing the whiplash effect.

2. Head restraint performance

Design of seats and head restraints has played a large part in the reduction of whiplash-related injuries and claims, and has been a significant area of research and product development. However, whiplash still continues to be the major source of insurance claims. Rating of head restraints and seats of cars in the market by independent organisations, such as IIHS (Insurance Institute

for Highway safety) in the United States and Thatcham MIRRC (The Motor Insurance Repair Research Centre) in the UK, and making the results public played a significant role in the improvement of head restraint designs. The automotive industry has found many effective ways of reducing the incidence of whiplash in rear-end collisions, with many unique and innovative designs for head restraints and car seats.

Initially, ratings were based on static measurements of the geometry of the head restraint. The 'backset' and 'topset' (Figure 3) of the head restraints were measured and classified. Backset of less than 40 mm and 'zero' topset were classified as 'good' by Euro NCAP. Over the time, the number of head restraints in the 'good' category increased as the manufacturers improved their designs. However, geometry alone was not sufficient to assess the ability of a head restraint to mitigate whiplash. Standardised dynamic sled tests and crash pulses using rear impact test dummies, such as BioRID, were developed. The intention of a dynamic test is to simulate a rear-end collision in which the target vehicle is struck while stationary or moving very slowly.

A number of criteria are used to assess the effectiveness of seats and head restraint systems in reducing whiplash; these include neck injury criteria, such as NIC and Nkm and other more specific measures, such as T1 (x-acceleration of thoracic vertebra 1), T-HRC (time to head restraint

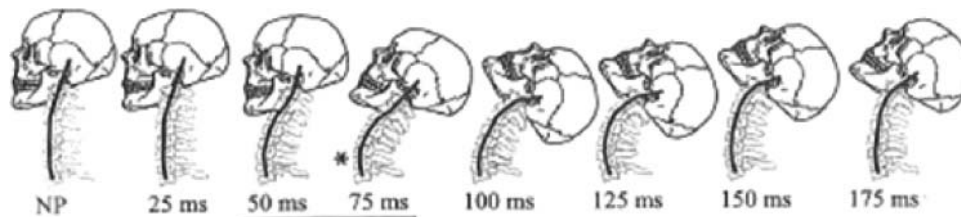


Figure 2. Schematic of a head and neck demonstrating time points during the occurrence of whiplash. A line is drawn through the vertebrae to highlight the curvature of the spine. A skull is shown for illustration only. NP: neutral posture [7].

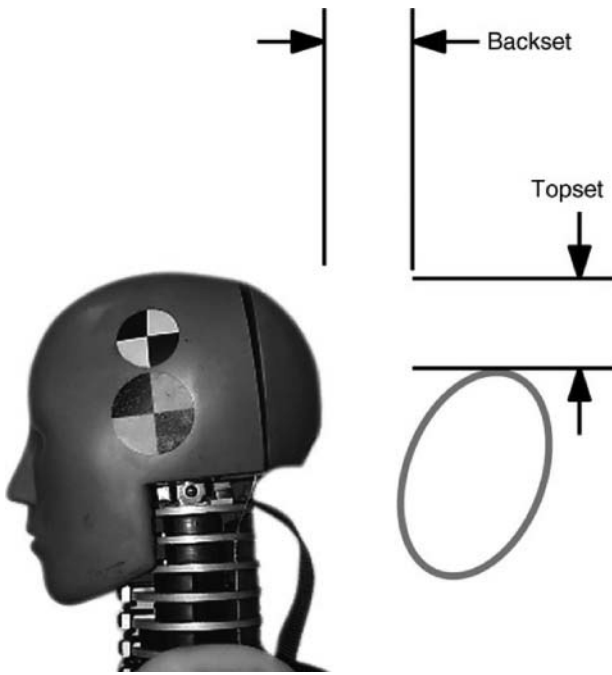


Figure 3. Diagram of geometric head restraint 'backset' and 'topset' [2].

contact), F_x (upper neck shear force), F_z (neck axial force) and rebound velocity. Within Europe, Euro NCAP regulates sled tests and provides motoring consumers with a realistic and independent assessment of the safety performance of car seats sold in Europe.

3. Seats and head restraints

There is a wide range of anti-whiplash seat and head restraints designs including designs with improved head restraint geometry, automatic smart head restraints, reactive head restraint and seats, proactive head restraints and bespoke seat foams to absorb impact energy.

There appears to be two main approaches to the design of various types of effective whiplash-reducing head restraints and car seats, based upon the ways they attempt to protect the occupant from suffering whiplash during a collision. They are as follows:

1. reducing backset and topset;
2. reducing relative motion between the head and torso.

The first group includes both reactive and proactive head restraints. In a rear-end collision, a typical reactive head restraint uses mechanical linkages to re-position the head restraint up and forward in order to provide support to the vehicle occupant's head, triggered by the occupant's torso applying pressure to the seat back when it moves backwards during a rear-end crash. Hence, the backset and topset are both reduced at the initial stages of the crash. A proactive system typically consists of a head restraint that automatically moves up and forward once the collision occurs, initiated by

the vehicle's crash sensors, again aimed at reducing the backset and topset. A smart head restraint system which adjusts itself to an optimum position can also be included in this group.

The second group requires the entire seat and head restraint design to react to the impact to reduce the relative motion between the head and torso and also absorb the energy of a rear-end crash. This could include translation of the seat and tilting of the seat back backwards somehow absorbing energy during the process.

In addition, seats with traditional fixed or adjustable head restraints with a good geometry but no apparent specific anti-whiplash technology may still provide good whiplash protection. Some use custom-designed foam technology in the seat to absorb the energy of the crash whilst allowing the occupant to engage the head restraint without excessive neck distortion.

3.1 Reactive head restraints

In 1996, Saab pioneered reactive head restraints and introduced the Saab active head restraint (SAHR) system to the market. Such systems utilise a four-bar linkage or an inverted slider crank mechanism in conjunction with a pressure plate inside the seat back. When the occupant moves rearward into the seat, their torso pushes against a plate that activates the linkage that moves the head restraint upward and forward as shown in Figure 4, in order to reduce the distance to occupant's head, thus, reducing the whiplash effect in a rear-end collision. The system uses springs to reset back to its original position so that no replacement of the seat is required. Independent studies into the effectiveness of head restraints and seat redesign in preventing neck injury in rear-end crashes have been conducted. It was found that active head restraints, which move upward and forward, reduced whiplash claims by an estimated 43% [5].

Designs of energy absorbing occupant seats for improving rear-impact protection and hence,

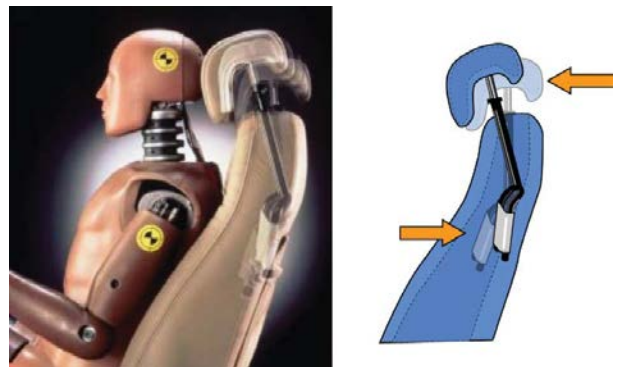


Figure 4. SAHR concept: as the occupant sinks into the seat back during a collision, their torso pushes against a plate and the mechanism is activated forcing the head restraint up and forward [16].

reducing the whiplash effect for vehicle occupants is proposed by Himmetoglu, et al. [8,9]. These are conceptual designs simulated dynamically by using a detailed head–neck model in conjunction with a human body model.

3.2 Proactive head restraints

Proactive head restraints (PAHRs) are designed with the aim of being able to prevent whiplash-related neck injuries caused by the differential movement of the head and neck, by reducing the backset and topset. Both Mercedes Benz and BMW have applied different types of PAHRs.

The Mercedes Benz NECK-PRO was introduced in 2005, the first of its kind as a sensor-controlled system, activated in the event of a rear-end collision (Figure 5). When the sensors detect a collision of this type above a predefined minimum level of severity, they release pre-compressed springs inside the head restraints which, in turn, release a four-bar parallel linkage which swings the head restraint 40 mm forward and 30 mm upward reducing the backset and topset. This provides the occupant's head the support required in a crash to prevent overextension of the cervical spine, thus reducing the risk of whiplash injury.

For successful operation of such a head restraint, the challenge was that the crash detection control systems must operate the linkage before the neck begins a whip-lash action.

In 2007, BMW introduced its PAHRs which are designed to move the head restraint up to 60 mm forward and up to 40 mm upward, activated and controlled by the car's airbag control unit, minimising the backwards movement of the head, to reduce the risk of neck injury. The head restraint uses a spring-driven mechanism which is



Figure 5. The movement of the NECK-PRO relative to the occupant's head [3].

activated by a pyro-actuator. Once the pyro-actuator ignites, it propels a release mechanism to allow the springs to move freely adjusting the head restraint in the forward and upward motion in order to protect the occupant from whiplash trauma.

3.3 Reactive seat

A reactive seat would aim to reduce the differential motion between the occupant's head and torso in a rear-end collision whilst absorbing impact energy. It is important to note that the seat itself is not sufficient on its own; a suitable head restraint must also be applied.

Autoliv designed a unique device, the Whiplash Protection System (WHIPS) for Volvo to mitigate whiplash injuries (Figure 6). The system works by reducing the differential motion between the occupant's head and torso using an expanding hinge on both sides of the seat pan and backrest. The hinge, which is primarily a four-bar linkage, absorbs the energy of a rear-end impact by initially translating the seat backwards and then rotating the seat back rearward by plastically deforming an element in the mechanical linkage in a controlled manner. The plastically deformed element needs to be replaced after a rear-end collision [15]. The WHIPS system is combined with a fixed, high-set head restraint, which is able to contact the occupant's head early enough during the collision before the neck and head have chance to move differentially, preventing stresses in the neck.

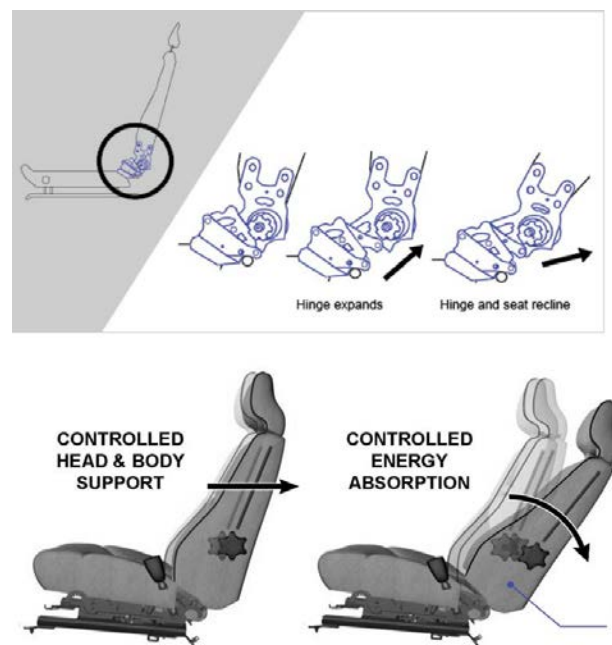


Figure 6. The WHIPS system hinge first expands and then reclines as a link plastically deforms, reducing the acceleration of the occupant relative to the car [11].

WHIPS has been estimated to reduce whiplash-related injuries by 49% [5].

The Toyota Whiplash Injury Lessening (WIL) device is a reactive seat. WIL operates when the occupant's back sinks into the seat, by supporting the occupants head and body simultaneously to minimise the potential effects of whiplash. Toyota achieved this by re-positioning the seat-back frame and head restraint and increasing the rigidity of the seat frame itself [21].

3.4 Passive seat

Passive seats tend to have normal seat geometry with no special features integrated into their mechanical design. Rather, the focus is on the material selection, in order to absorb the impact energy transferred during a collision from the occupant into the seat using special foams engineered for such a purpose. The idea is that it should allow the occupant to engage the head restraint without excessive neck distortion. However, very little information is available in the public domain as to the properties of the materials used.

Passive seats with good energy absorbing characteristics are known to have high ratings, however, it should be noted that the European NCAP ratings suggest that the reactive head restraints and seats are generally the most effective solutions, consistently scoring higher than passive foam technologies and proactive devices. Thus, there is a good potential within the automotive industry to combine passive foam technologies with other whiplash mitigating concepts to gain even higher ratings.

3.5 Smart head restraint

A unique head restraint system which detects the position of the occupant's head when seated in the car was successfully demonstrated the concept at Loughborough University and exhibited at the 19th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Washington DC, 6-9 June 2005 [1]. The system uses ultrasonic sensors, actuators and a control algorithm to move the head restraint into an optimum position. The demonstrator proved that the concept of a sensor-based system was a feasible and effective solution.

4. Concept development

A number of concepts that combine a reactive seat with a reactive head restraint have been generated and evaluated. For the brevity, only the selected concept is reported here. The chosen concept

uniquely integrates the following reactive systems in a complete whiplash mitigating seat design:

1. A mechanical linkage system built into the head restraint to be activated by the upward motion of the link inside the seat back.
2. A mechanical linkage system built into the seat back whereby the force of the occupant would slide a rod upwards in a controlled manner to activate the head restraint.
3. A mechanical linkage that allows the whole seat to tilt backwards in a controlled manner to reduce the differential motion between the occupant's head and torso, possibly aided by a seat damper.

All these concepts are purely mechanical and reactive in nature, operate only when the vehicle receives a rear-end collision. Mechanisms operate instantly and simultaneously when the body of the occupant begins to push against the seat back. The head restraint and seat should be aided by a seat damper to absorb the crash energy whilst controlling and limiting the reclining motion of the seat in conjunction with a locking mechanism to prevent rebound. The design of the dampers and energy-absorbing seat back foam will not be considered here, as the aim of this paper is the conceptual design: the mechanical systems.

The design should be reusable and add no significant weight to the vehicle and should not adversely affect the fuel economy. The chosen concept shall bear little addition to the overall cost of a standard car seat, making the device affordable for all range of cars. The concept should be designed with mass production in mind, not over complex in its design, and easy to manufacture and assemble.

4.1 Head restraint design

A reactive head restraint system is designed with the view to achieve a zero head-offset during a rear-end collision, in order to reduce the time in which the occupant's head makes contact with the head restraint. The head restraint is split into two parts, a bucket to which the four-bar parallel linkage is attached and the cushion that is attached to the coupler of the linkage. A slider, which moves along the lower binary link, is attached to the upper end of the activation mechanism inside the seat back, couples the two linkage systems (Figure 7). The mechanical linkage concept is created using SAM 6.1 (Synthesis and Analysis of Mechanisms) software which is used for design, analysis and optimisation of mechanisms. It should be noted that the concept is shown in a simplistic two-dimensional format, to be consistent with SAM.

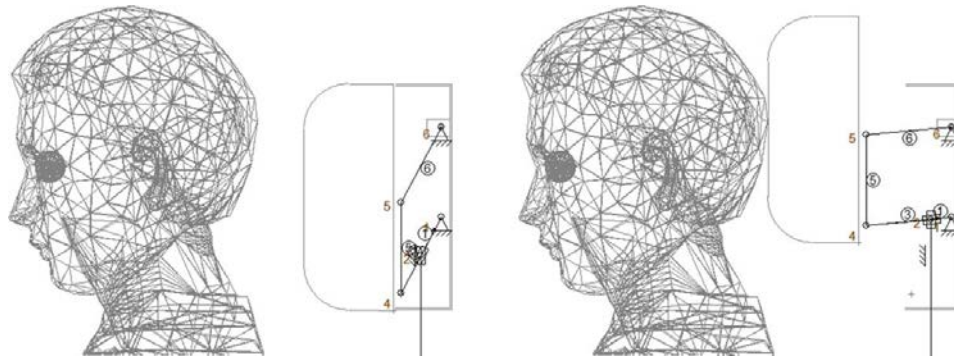


Figure 7. Reactive head restraint concept before and after activation.

4.2 Seat-back mechanism

The linkage inside the seat back is a slider crank mechanism with the slider pushing up a rod in the vertical direction when the occupant's body applies pressure on the plate at the pin joint between the crank and the connecting rod. Figure 8 shows the linkage inside the seat as generated by SAM (pressure plate is not shown). When the link in the seat back moves upwards, reacting to the motion of the torso, it operates the parallel linkage in the head restraint moving its cushion upward and forward.

4.3 Reactive seat design

The purpose of a reactive seat is to reduce the differential motion between the head and torso. The seat should be capable of rotating rearwards in a controlled manner to achieve this. This concept works in the same way as the head restraint, whereby the seat pan is attached to the coupler of a four-bar linkage, allowing the seat to rotate rearwards as the occupant 'sinks' into the seat back (Figure 9). The backward motion of the seat needs to be limited, this could be achieved by using bespoke elastomeric dampers which also absorb energy of the impact (not considered here).

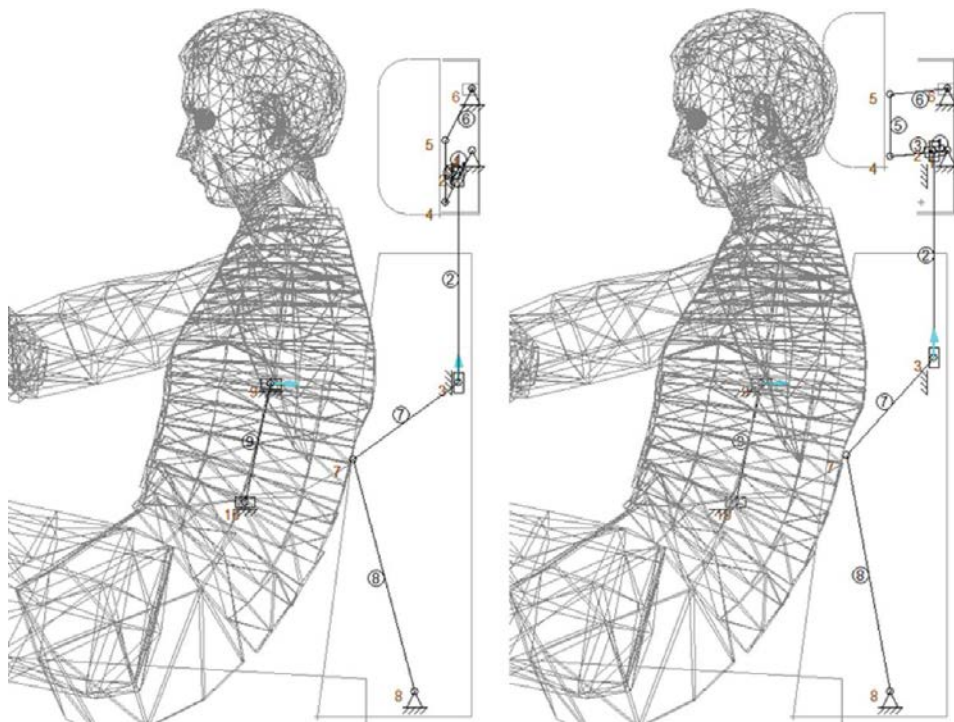


Figure 8. Reactive head restraint and activation system inside the seat back.

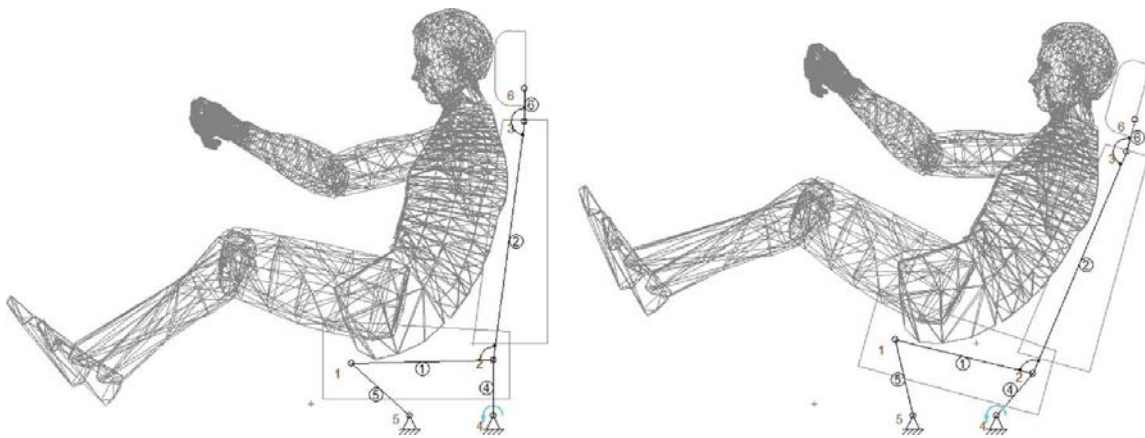


Figure 9. Reactive seat concept.

5. Concept models

A separate demonstrator each for the head restraint and for the reclining seat was created. It should also be noted that the human model depicted in Figures 7-10 and 12 features as a

rigid body, where no deformation takes place.

An acceleration pulse was created for the concept model by assuming acceleration to increase linearly from 0 to 10.5 g over the time

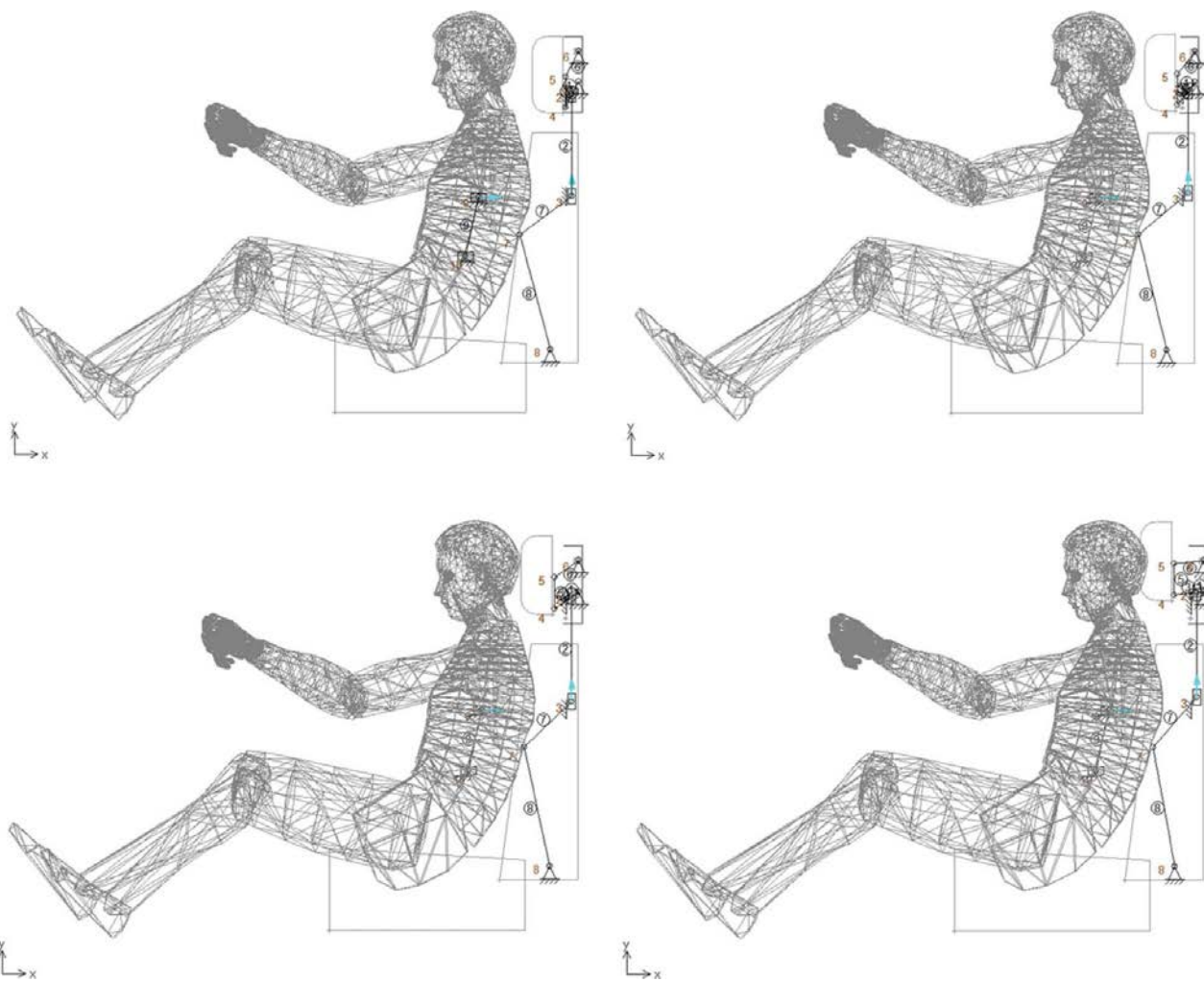


Figure 10. The motion simulation over a time period of 0-12 ms showing that the head restraint moves into a position reducing the distance to the occupant's head.

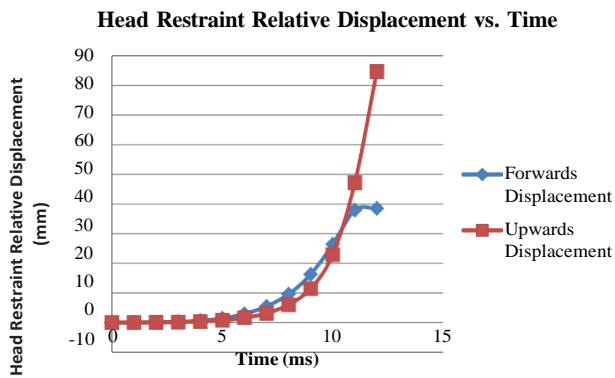


Figure 11. Head restraint relative displacement.

Period of 27 mms as per the standard Euro NCAP high-severity pulse. The acceleration input is used for the human body model in rearward direction with respect to the seat.

5.1 Head restraint system

Figure 10 shows the motion of the head restraint in four steps as the body sinks into the seat back. The results from the simulation show that the human's head makes contact with the head restraint within just 12 ms. Figure 11 shows the relative displacement of the head restraint with respect to the initial position in both the x-axis and y-axis.

It can be seen that the head restraint is capable of moving the required distance of 40 mm just as it makes contact with the human head within 12 ms, also moving upwards by more than 40 mm.

These results would suggest that the head restraint concept would be capable of reducing the occurrence of whiplash as it moves into an optimal position well before 25 ms when it is believed that the whiplash phenomena will initiate as shown in Figure 2.

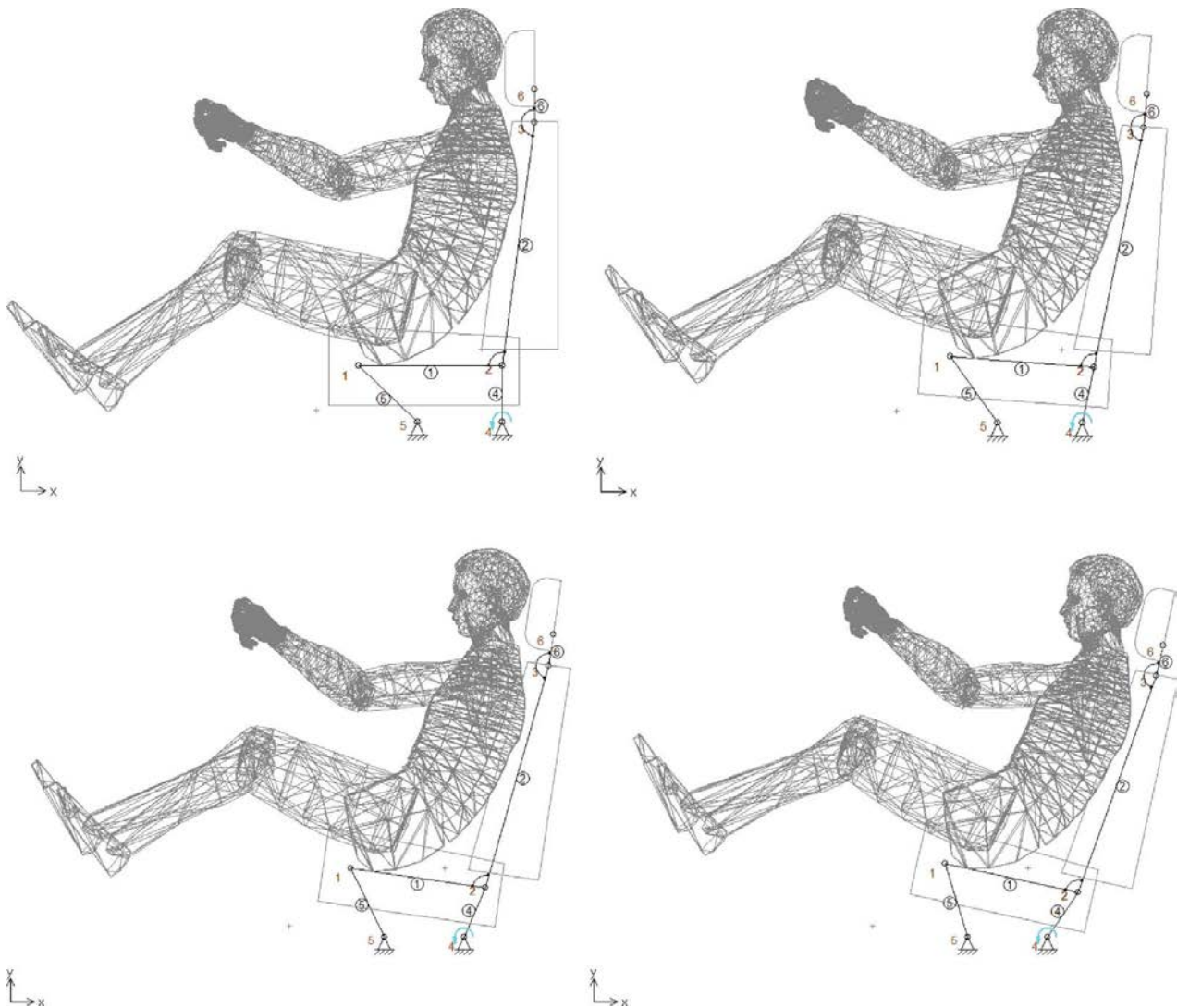


Figure 12. The motion simulation of the reactive seat demonstrator over a time period of 0-25 ms showing that the whole seat reclines.

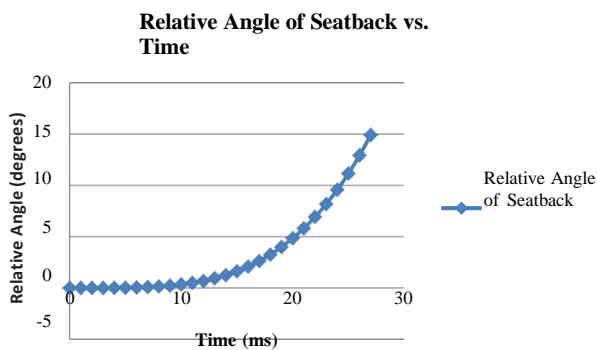


Figure 13. Relative angle of seat back.

5.2 Reactive seat system

Figure 12 shows how the reactive seat concept would work, reclining backwards under the pressure from the torso to reduce the differential movement between the torso and the head. The model demonstrates a reclining motion by an angle of 15 degrees, as shown in Figure 13, matching that of the Volvo WHIPS, in a period of 27 ms. When this motion is combined with the forward and upward displacement of the head restraint it is expected to provide an improved whiplash protection.

6. Conclusions

A novel concept that integrates a reactive head restraint system with a reactive seat has been proposed. Currently, there is no product in the automotive market that integrates the two concepts. The combined system is capable of moving the head restraint upwards and forwards meeting the position requirements within 12 ms well before hyperextension of the neck occurs. Hence, the likelihood of whiplash-related injuries in a rear-end collision could potentially be reduced with this integrated design.

The reactive seat system was designed to recline by 15 degrees, the same as the Volvo WHIPS. The seat reclines within 27 ms, and thus, the chance of reducing the relative motion between the head and torso before the whiplash mechanism has time to have an effect. The seat could also be fitted with an appropriate elastomeric damper to absorb energy further reducing the effect on the occupant.

The cost of such a safety seat and the head restraint system should be an affordable option for all manufacturers and hence, beneficial to all consumers in the automotive industry. The concepts presented could form the basis for a prototype product for and automotive seat manufacturer to assess the potential of the concept to mitigate whiplash in rear-end collisions.

Disclosure statement

No potential conflict of interest was reported by the authors.

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