REDUCTION OF HEAD ROTATIONAL MOTIONS IN SIDE IMPACTS DUE TO THE INFLATABLE CURTAIN - A WAY TO BRING DOWN THE RISK OF DIFFUSE BRAIN INJURY

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ABSTRACT

Diffuse brain injuries are very common in side impacts, accounting for more than half of the injuries to the head. These injuries are often sustained in less severe side impacts. An English investigation has shown that diffuse brain injuries often originate from interior contacts, most frequently with the side window. They are believed to be mainly caused by quick head rotational motions.

This paper describes a test method using a Hybrid III dummy head in a wire pendulum. The head impacts a simulated side window or an inflatable device, called the Inflatable Curtain (IC), in front of the window, at different speeds, and at different impact angles. The inflated IC has a thickness of around 70 mm and an internal (over) pressure of 1.5 bar. The head was instrumented with a three axis accelerometer as well as an angular velocity sensor measuring about the vertical (z) axis. The angular acceleration was calculated. The head impact speeds ranged up to 7 m/s, a speed at which the Inflatable Curtain barely bottoms out. The recorded data for linear acceleration, angular acceleration and angular velocity were compared with corresponding threshold values found in the literature.

It was concluded that the Inflatable Curtain has the potential to substantially decrease the risk of sustaining diffuse brain injuries. The IC reduced the maximum linear acceleration and HIC up to 70% and the peak angular acceleration up to 70%, depending on the contact angle between the head and the IC. The peak angular velocity was reduced up to 30%.

INTRODUCTION

Head injuries can be divided into skull fractures, focal brain injuries and diffuse brain injuries. The latter type is the most common. Gennarelli *et al.* (1987) found that over half of the hospitalized patients for head injuries in the United States suffered from diffuse brain injuries. One third of the injuries were fatal. Morris *et al.* (1993) found in another study that 60% of AIS 2+ head injuries in side impacts were of the diffuse brain injury type.

The diffuse brain injuries originate mainly from contact with the interior of the car, especially with the side window (Morris *et al.*, 1993). It was found in the same survey that diffuse brain injuries of AIS2+ level occurred in less severe side collisions with a mean delta-velocity of 32 km/h, than all head injuries of AIS2+ level, with a mean delta-velocity of 43 km/h.

Diffuse brain injuries are believed to be caused by quick rotational motions resulting in critical strains of the axons. These injuries are known as diffuse axonal injuries (DAI). The injuries can be widespread in the brain without any structural disruptions (Gennarelli *et al.*, 1989).

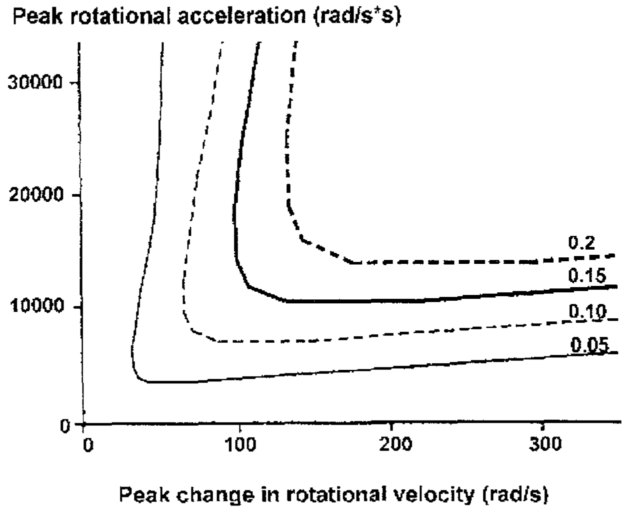
According to a study by DiMasi *et al.*, (1995) a pure translational acceleration of the head will induce very little strain, while a pure rotational acceleration will induce considerably more strain. A combination of translational and rotational accelerations will induce more strain than the rotational acceleration alone. Viano (1997) found similar high strains due to pure rotational acceleration. However, he also found greater strains with pure translational acceleration than DiMasi.

The diffuse brain injuries can cause loss of consciousness during a short or longer period of time. When regaining consciousness there may be irreversible injuries to the axons with loss of physical functions as well as changes of personality (Aldman, 1996).

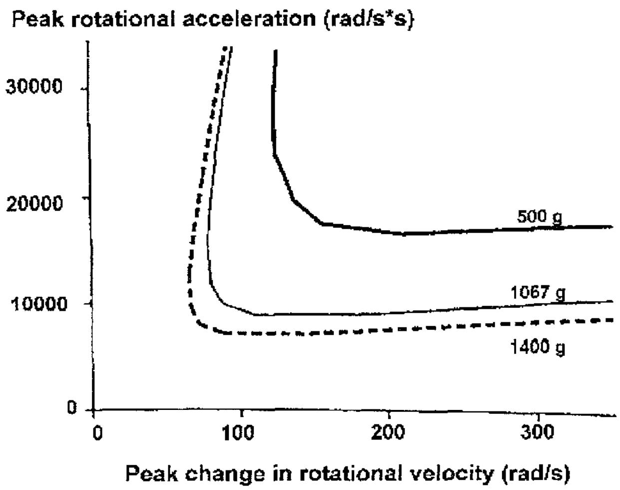
Injury assessment

The severity and type of diffuse brain damage appears to depend on the magnitude, the duration and the onset rate of the angular acceleration. A short duration of rotational acceleration will require a very high magnitude in order to cause damage to the brain tissue. Conversely, increased acceleration duration can cause brain damage at lower rotational accelerations. When the duration and the amplitude of the acceleration increase, the strain will occur deeper into the brain and cause axonal damage (Gennarelli,1987).

Margulies *et al.* (1992) proposed tolerance levels for diffuse brain injuries in lateral rotational acceleration motions (acceleration about the x-axis). The tolerance is described by the peak angular acceleration (sinewave) and the peak change in angular velocity, which can be reached before a critical level of strain is exceeded. The peak change in angular velocity is the maximum of the integration of the angular acceleration. The strain is linearly increasing with the load and exponentially increasing with the brain size (Margulies *et al.,* 1989). Concussion can be compared with a strain level of 0.05, while tissue disruption occurs at a strain level of 0.2 (Gennarelli *et al.*, 1989).



a.



b.

Figure 1. The graphs show the DAI (Diffuse Axonal Injury) thresholds for various strains (Fig. 1a) and for various brain masses (Fig. 1b); peak rotational acceleration as function of peak change in rotational velocity. Redrawn from Margulies *et al.*, 1992.

Gennarelli *et al.* (1987) performed a study concerning the directional dependence of DAI. They concluded that non-centroidal rotation about the longitudinal horizontal x-axis (center of rotation in the lower cervical spine) resulted in the longest traumatic coma. The centroidal rotation about the vertical z-axis was the second worst and non-centroidal rotation about the lateral horizontal y-axis resulted in the shortest traumatic coma (center of rotation in the lower cervical spine).

The Head Injury Criterion (HIC) is based on linear acceleration of the head and can only predict injuries due to forces which are directed through the center of gravity of the head. HIC does not take into account the rotational motion of the head (Gennarelli, 1987).

The aim of this study was to determine the influence the Inflatable Curtain has on the head rotational motion about the vertical z-axis and on the linear acceleration in angled head to side window impacts.

METHODS

Test setup

The test method was based on a Hybrid III dummy head in a wire pendulum. The head was attached above the center of gravity and it was permitted free rotation about the vertical z-axis.

No neck muscle activity was simulated. In these tests, the maximum angular acceleration was reached within 25 ms and the maximum angular velocity within 35 ms. The reaction time of the muscles are normally longer, up to 120 ms (van der Horst *et al.*, 1997). The head was turned up to 30° from its normal forward direction. For a human being, the head is moving freely the first 47°, if the muscles in the neck are not strained (White *et al.*, 1978).

The Inflatable Curtain was mounted on a fixture. A 3 mm thick aluminum plate was attached to the fixture, in order to simulate a side window (Figure 2). The aluminum plate was perpendicular to the ground. A rubber strip was placed between the aluminum plate and the fixture, in order to try to simulate the conditions for a car side window.

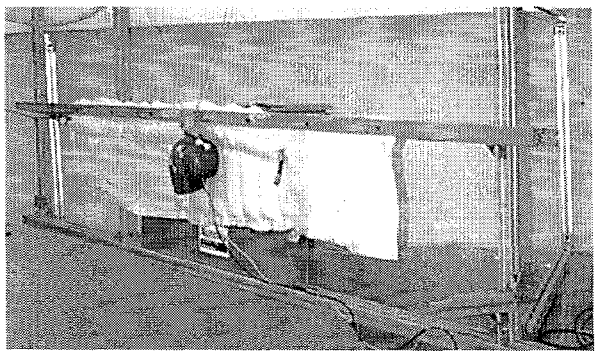


Figure 2. The test rig.

The side window had an angle α related to a reference plane (Figure 3). The angle (α) was 30° in most tests, but an angle of 45° was also tested. The 30° angle represents the head motion for the driver in a 10 o'clock side impact and the same for the passengers head in a 2 o'clock side impact.

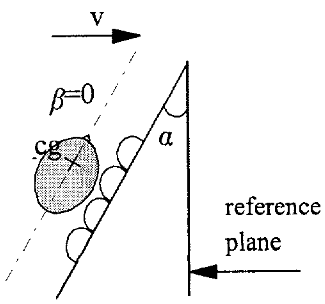


Figure 3 . The test setup from above.

The angle β was defined as the angle between the side window and the center line (x-axis) of the head, through the center of gravity and the nose. The angle β was zero, when the head was parallel with the side window (Figure 3). In this position, it should be noticed that the normal force was not directed through the center of gravity, since this point was located slightly closer to the forehead. The angle β was altered in some of the tests between -30° and +30° (Figure 4).

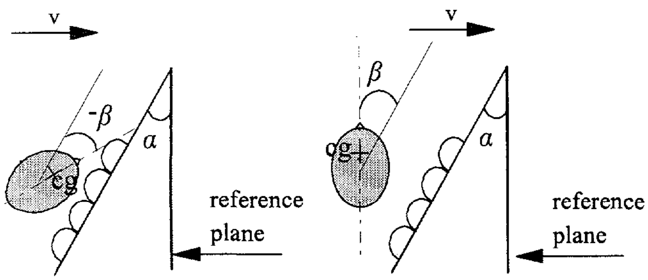


Figure 4. The figure shows how the angle β between the head and the "window" was altered in the tests.

Instrumentation - The head was instrumented with an angular velocity sensor (ARS-01 made by Ata Sensors, USA) and a standard triaxial accelerometer at the center of gravity. The signals were filtered with CFC1000. The angular acceleration was calculated and filtered with CFC180.

A film video camera (KODAK EM, 1000 Hz) was mounted above the head.

The Inflatable Curtain - The IC (Figure 2) had a volume of 12 l and a thickness of 70 mm. It was inflated with compressed air. The internal (over) pressure was 1.5 bar and measured in the front part of the filling duct.

There was no ventilation of the IC except for a small amount of air leaking through the fabric.

The IC had an outer silicon coating. In some tests talc was applied to the surface to study the effect of the friction.

Procedure

The head was dropped from an elevated level, in order to reach a specific velocity (v) at the time of the impact to the "window". The velocity was 3 m/s, 5 m/s or 7 m/s. The velocity of 7 m/s can be equivalent to the impact speed of the head into a fixed object in a 30 km/h car-to-pole/tree collision.

Tests were performed both with and without the IC inside the "window". The influence of the friction of the fabric at various levels of pressure was also tested.

When the head form contacted the IC, there was no simulated lateral bending of the neck. The vertical axis of the head was parallel with simulated window.

RESULTS

Rotational motions

The use of the IC reduced the peak angular acceleration by about 60-70% (Figure 5). The peak angular velocity was reduced less. The reduction being between 2-30% depending on the angle between the head and the IC.

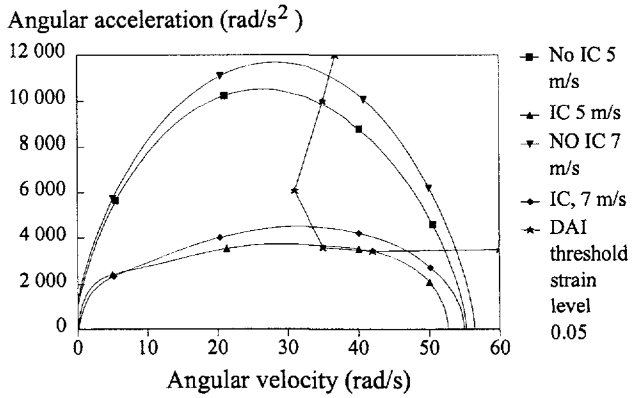


Figure 5. The angular acceleration as function of the angular velocity (simultaneous values) and the peak values. The angle (β) between the head and the IC was 30°. The DAI threshold curve (0.05 strain level) is redrawn from Margulies *et al.* (1992).

Figure 5 shows simultaneous values of the angular acceleration and the angular velocity. The results will be presented as peak angular acceleration and peak angular velocity. It should be noticed that the two peaks do not occur at the same time.

When the impact velocity was increased from 5 m/s to 7 m/s, the peak angular velocity increased 5-10% and the peak angular acceleration 15-25% depending on the angle β between the head and the simulated window, with or without the IC (Figure 6).

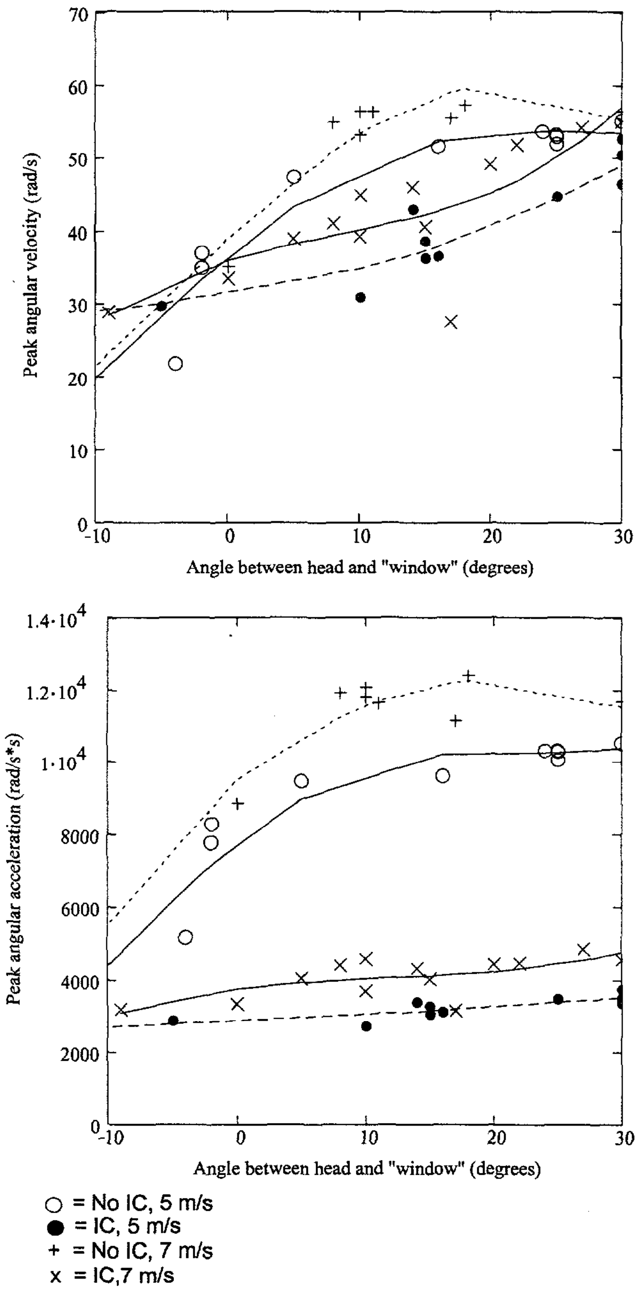


Figure 6. The peak angular velocity and the peak angular acceleration as a function of the angle (β) between the head and the "window", with and without IC, at different impact velocities. The angle (α) between the IC and the reference plan was 30°.

The angle (α) between the reference plane and the simulated side window were tested at 30° and 45°, with the head parallel to the reference plane. Without the IC, the angular acceleration about the z-axis decreased about 35% when the angle increased from 30° to 45° angle, independent of the velocity of the head. With IC, the angular acceleration increased only about 5%.

The angle (β) between the head and the "window" was varied between -30° and +30° (see Figure 4). The minimum values were reached at an angle of -20°. That was the angle at which the normal contact force was directed through the center of gravity. The angular acceleration and the velocity both increased with the increase of the angle β (Figure 7).

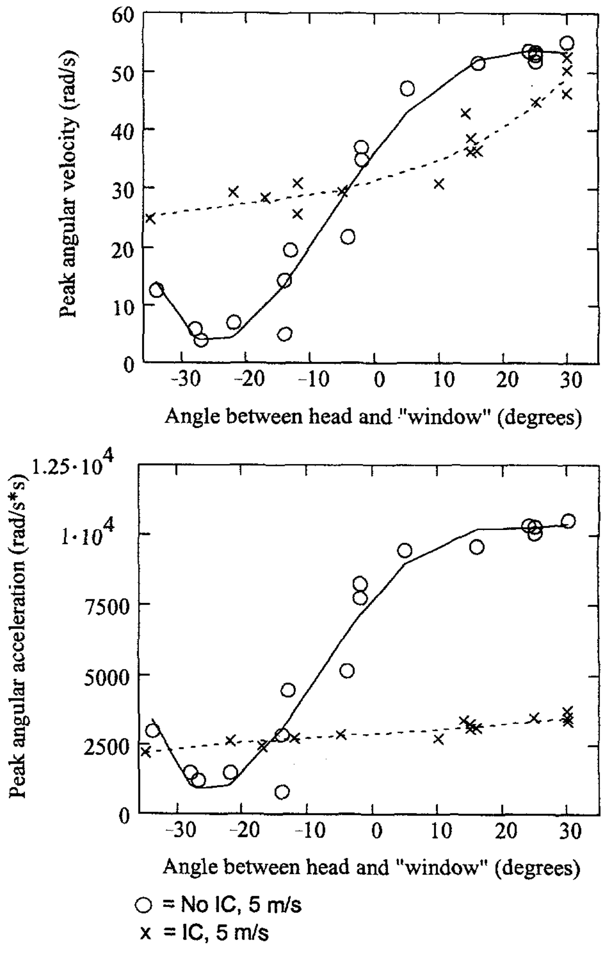


Figure 7. The absolute value of the peak angular velocity and peak angular acceleration as function of the angle (β) between the head and the "window", at a contact velocity of 5 m/s.

The angular acceleration, however, did not increase in the same way with the IC as without the IC, when the angle between the head and the "window" was increased

(Figure 7). At -20° the peak angular acceleration and velocity were almost zero, when there was no IC.

Linear motions

The IC reduced the linear acceleration up to 70% (Figure 8).

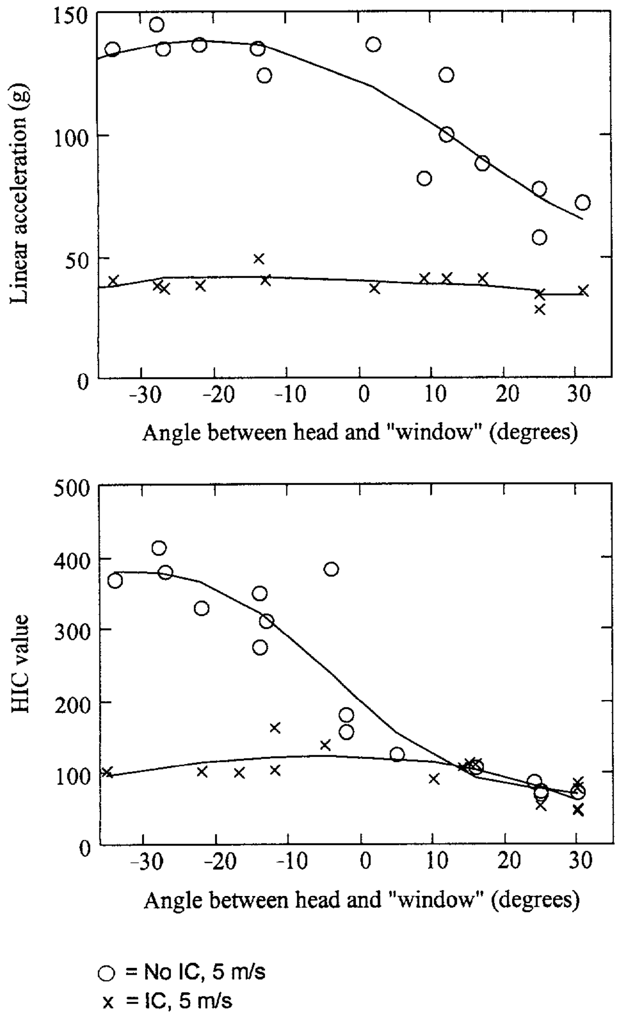


Figure 8. The linear acceleration and the HIC as function of the angle (β) between the head and the "window".

The HIC shows the same characteristic as the linear acceleration, with a reduction up to 70%. The HIC increased as the angle β between the head and the IC decreased (Figure 8). The increase was much smaller with the IC.

DISCUSSION

Rotational motions

__**Inflatable Curtain**__ - The head angular acceleration was reduced due to the relative "soft" spring characteristics of the IC compared to the "stiff" side window. The angular velocity was mainly influenced by the damping of the IC, which was limited at these impact velocities and impact angles. Moreover, the duration of the rotation was longer with the IC than without, which gave the head more time to reach the angular velocity, despite the lower rotational acceleration.

Figure 5 shows that the risk of diffuse brain injury was mainly reduced by the reduction of the angular acceleration due to the IC.

__**Angle between the IC and the reference plane**__ - The angular acceleration decreased as the angle (a) increased from 30° to 45°. The angle a had an influence on the head velocity component perpendicular to the IC. The velocity v_y thus decreased as the angle a increased (Figure 9), which explains the reduction of the angular acceleration.

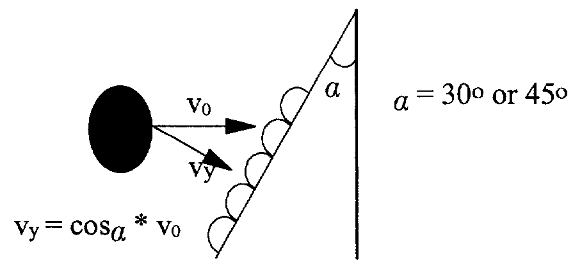


Figure 9. Test conditions.

The peak angular velocity was marginally affected by the change of the angle a from 30° to 45°. The limited energy absorption of the IC in these test conditions means that the kinetic energy of the head form before the impact is transformed to rotational energy after the impact.

__**Angle between the head and the IC**__ - The torque, the normal contact force times the distance between the contact point and the head center of gravity point, increased with the angle β. This directly increased the angular acceleration. The normal forces were obviously larger than the friction forces.

When the head first came in contact with the IC, it penetrated the IC a couple of millimeters without any large force (15% of the maximum force). The force then increased and the head started to rotate. The distance between the point of contact and the center of gravity, when the head had an angle β of 30° to the side window, was about 7 cm. The effective distance, however, decreased, when the head started to compress the IC. This can explain why the angular acceleration did not vary so much for different β angles with the IC as without the IC.

Pressure of IC - A range of different pressures were tested (between 0.5 bar and 2.0 bar). The angular peak acceleration and velocity decreased both with a reduction in pressure (Figure 10).

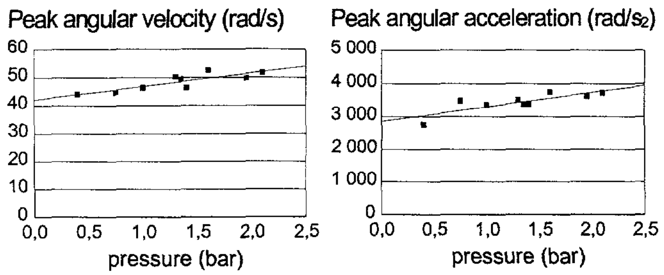


Figure 10. Influence of the pressure of the IC. The angle (β) between head and IC was kept to 30°. The head impact velocity was 5 m/s.

The angular acceleration and angular velocity decreased by about 20%, when the pressure was decreased 75% (from 2.0 bar to 0.5 bar). In order to avoid a bottoming out of the IC at higher impact velocities (7 m/s), the pressure needs to be about 1.5 bar.

Friction - Some additional tests were performed with an IC applied with talc on the surface in order to reduce the friction. The reduction in friction was approximately 80%, from 3.1 to 0.7, when measuring the friction between the fabric and a piece of glass.

The peak angular acceleration increased only between 5% and 10% with the higher friction, independent of the angle between the head and the IC. The angular velocity showed the same small dependency on the friction as the angular acceleration.

Linear motions

The maximum HIC and the maximum linear acceleration were reached, when the angular acceleration and angular velocity had their lowest values. The linear acceleration had its maximum, when the contact force was directed through the center of gravity, which at the same time resulted in the lowest angular acceleration. Vice versa, when the contact point was applied further away from the center of gravity, the linear acceleration decreased and the rotational acceleration increased (Figure 7 and 8).

DiMasi *et al.* (1995) noticed a combined effect between translational and rotational accelerations, when the translational acceleration resulted in a HIC between 800 and 900. In these tests the maximum HIC value was less than 400. This combined effect could not be estimated from these test results. However, it is possible that the strain effects in a human brain at these levels of linear acceleration are small.

CONCLUSIONS

The study has shown that the Inflatable Curtain reduces the angular acceleration as well as the angular velocity of the head in angled head to side window impacts. There was a 2-30% reduction of the peak angular velocity and a 60-70% reduction of the peak angular acceleration in the tests performed. The linear acceleration was reduced up to 70%. It is therefore believed that the IC has the potential to substantially reduce the risk of sustaining diffuse brain injuries in side impacts.

The maximum angular acceleration and angular velocity were both dependent on the perpendicular impact velocity of the head to the side window/IC.

The angle between the head and the IC/window had an influence on both the angular acceleration and angular velocity. However, the influence of the angle was much larger without IC than with.

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