THE ROLE OF SEATBACK AND HEAD RESTRAINT DESIGN PARAMETERS ON REAR IMPACT OCCUPANT DYNAMICS

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ABSTRACT

Although typically classified as AIS 1, whiplash injuries continue to represent a substantial societal problem with associated costs estimated at over $5 billion annually in the US. The primary objective of this study was to determine the effects of seatback and head restraint design parameters on occupant response in rear impact.

Rear impact sled tests were conducted using the Hybrid III mid-sized male (50M) dummy seated in a modified production seat, which allowed for the adjustment of recliner stiffness, seatback cushion stiffness, and head restraint height. Instrumentation provided measurements of neck forces and moments, head motion relative to the torso, seatback rotation, and head contact. An on-board digital video camera recorded dummy kinematics. Results from this study indicate that the risk of whiplash injury is not simply related to head restraint position, but is dependent on a combination of factors related to both head restraint and seatback design.

INTRODUCTION

Although typically classified as AIS 1, whiplash injuries continue to represent a substantial societal problem with associated costs in the US estimated by the National Highway Traffic Safety Administration (NHTSA) at $5.2 billion annually [1]. Despite years of research by numerous investigators, the specific mechanisms of whiplash injuries continue to be a source of debate within the automotive safety community [2-7].

Most researchers agree that whiplash injuries are related to the relative motion between the head and torso, and that the reduction of this relative motion will lead to a decrease in the incidence of these injuries. Further, it has been shown that the relative motion between the head and neck is greatly affected by seat design, and in particular by the position of the head restraint relative to the head [6-7]. Head restraint height and backset (horizontal distance between the head and head restraint) are the two seat design parameters most commonly used to evaluate the response of an occupant to a rear impact collision.

Svensson *et al* [2] investigated the relationship between head restraint position and the occurrence of injuries to the cervical nerve roots. They have demonstrated through a series of porcine experiments that the relative motion between the head and neck during a rear impact causes the lower cervical spine to go into local extension while the upper cervical spine goes into local flexion. This difference in curvature causes pressure variation and fluid movement within the spinal canal, which is believed to generate injurious stresses and strains to the exposed tissues.

Other researchers have focused on the vertebral level effects of the relative motion between the head and torso. Kaneoka *et al* [3] and Ono *et al* [4] have conducted rear impact tests using volunteers and cineradiography. They have shown that during a rear impact, relative motion between adjacent vertebrae may cause impingement of the lateral facets and pinching of the surrounding soft tissues. Yoganandan *et al* [5] have also demonstrated this pinching mechanism using a cadaveric head-neck experimental model on a mini-sled system driven by an impact pendulum.

Siegmund *et al* [6] conducted a series of volunteer tests on 42 subjects, including 21 males and 21 females. They performed a multiple linear regression analysis to determine the relative influence of various factors related to the subject and vehicle. Their results showed that vehicle speed change and relative head restraint position explained the largest proportion of the observed variation in peak occupant kinematic response.

Kleinberger *et al* [7] evaluated the effect of head restraint position on occupant response using a computational model. Their results showed that the forces and moments acting at the top of the neck, and also the acceleration and rotation of the head relative to the torso decreased as the head restraint was moved higher and closer to the back of the occupant's head.

Seatback properties, such as cushion stiffness and energy absorption, have also been identified as potential factors affecting occupant response to rear impact. Welcher and Szabo [8] evaluated the performance of five seats with varying properties using volunteer subjects. Head restraint position was found to be most influential on occupant head-neck kinematics. Head restraint height and backset were found to be significantly correlated with rearward translational motion of the head relative to the torso. Backset was found to be significantly correlated with the relative extension of the head, while head restraint height was significantly correlated with the head acceleration relative to the torso during the flexion phase of the impact.

Several different criteria have been proposed by researchers in an attempt to predict the occurrence of whiplash injuries. Since there is currently no consensus on any of these criteria, this paper will include calculations for several of the more commonly used criteria. Bostrom *et al* [9] proposed the Neck Injury Criterion (NIC), which is based on the Navier Stokes equations and the assumption that fluid flow within the spinal canal causes pressure gradients that are injurious to the nerve roots. The criteria is represented by the formula

$$NIC = 0.2a_{rel} + v^2{}_{rel} \qquad (1)$$

where a_{rel} and v_{rel} are the acceleration and velocity of the occipital condyles relative to the T1 vertebra, respectively.

Kleinberger *et al* [10] proposed the N_{ij} neck injury criteria, which combines the effects of forces and moments acting at the occipital condyles. This criteria actually consists of four separate criteria for predicting injuries related to the four primary modes of cervical loading, namely compression-flexion (N_{CF}), compression-extension (N_{CE}), tension-flexion (N_{TF}), and tension-extension (N_{TE}). For rear impact testing, the N_{TE} criterion is generally the most critical. It is important to note that the N_{ij} criteria were initially created to predict serious AIS 3+ injuries and are only useful in a qualitative manner for predicting minor whiplash injuries. The tension-extension criterion is represented by the formula

$$N_{TE} = \frac{F_Z}{F_{\text{int}}} + \frac{M_Y}{M_{\text{int}}} \qquad (2)$$

where F_Z and M_Y are the axial force and extension moment calculated at the occipital condyles, respectively. F_{int} and M_{int} are the normalizing critical values for the force and moment, respectively. The currently accepted critical values for the 50M Hybrid III dummy in tension-extension are F_{int}=6806N and M_{int}=135Nm [11] for AIS 3+ injuries.

Schmitt *et al* [12] proposed a modified version of the Nij criteria, called the N_{km} Criteria, which combines the effects of shear force and flexion-extension moment in the upper cervical spine. Using "e" for extension, "f" for flexion, "a" for anterior shear, and "p" for posterior shear, the four individual criteria are N_{ea}, N_{ep}, N_{fa}, and N_{fp}. The criteria is represented by the formula

$$N_{km} = \frac{F_x}{F_{\text{int}}} + \frac{M_Y}{M_{\text{int}}} \qquad (3)$$

where F_X and M_Y are the shear force and extension moment measured at the upper neck load cell, respectively. F_{int} and M_{int} are the normalizing critical values for the shear force and moment, respectively. The critical values are M_Y = 47.5 Nm in extension, M_Y = 88.1 Nm in flexion, and F_X = 845 N in both anterior and posterior shear. These criteria were developed to assess the risk of low severity whiplash injuries using the Hybrid III dummy with a TRID neck. The authors state that these values may need to be revised for use with other dummies.

Prasad *et al* [13] conducted a series of rear impact sled tests with different seat designs to determine the relationships between seat design parameters and the forces and moments measured at the upper and lower neck load cells. Results indicated that the extension moment measured at the lower neck load cell was most sensitive to seat design and crash severity.

Finally, the head rotation relative to the upper torso is also presented as a potential injury criteria related to rear impact whiplash injuries. This is based on the premise that cervical injuries are related to the relative motion between the head and torso, and that controlling this relative motion should reduce the incidence of whiplash injuries. Ideally, both the relative translations and rotations should be measured. However, it is difficult to measure the relative translation without requiring video analysis, which is impractical for certain types of testing.

Viano *et al* [14] conducted a series of rear impact tests with the BioRID and Hybrid III dummies using several different production seats. Measured dummy responses were compared with insurance claims data. The authors proposed a Neck Displacement Criterion (NDC), which is based on the relative displacement and rotation between the occipital condyles and the T1 vertebrae as compared with the natural range of motion. This criterion was proposed as a supplement to other existing criteria until the mechanisms of whiplash injury are better understood.

This paper evaluates the effects of seatback and head restraint properties on the occupant response to a rear impact collision. The injury criteria described above are used as a means of comparing the occupant responses under the various test configurations. For the seatback cushion stiffness evaluation, only relative head rotation is presented since the load cell data was not collected for this series of tests.

EXPERIMENTAL METHODS

A production automotive seat (1999 Toyota Camry) was modified to allow the rotational recliner stiffness, head restraint height, and backset to be adjustable over a wide range. The normal recliner mechanism was replaced with a simple pin joint to provide free rotation at the hinge joint. Rotational stiffness was provided by two spring-damper assemblies externally mounted to the rear of the seatback. Stiffness was varied by changing the set of coil springs and/or their location relative to the hinge joint.

To provide a repeatable test system and avoid any permanent deformation, the seatback frame structure was reinforced with sheet metal and steel channels to provide attachment points for the spring assemblies. The head restraint supports were also modified to allow adjustment in both the horizontal and vertical directions. Figure 1 shows the modified seat with the attached spring-damper assemblies.

Tests were conducted on a Via Systems deceleration sled using the Hybrid III mid-sized male (50M) dummy seated in a rear-facing seat. A sinusoidal sled pulse with a nominal impact speed of 17 kph was used that fit within the FMVSS 202 dynamic testing corridor. The peak acceleration and duration of the pulse was 9.0 g's and 90 msec, respectively, as shown in Figure 2.

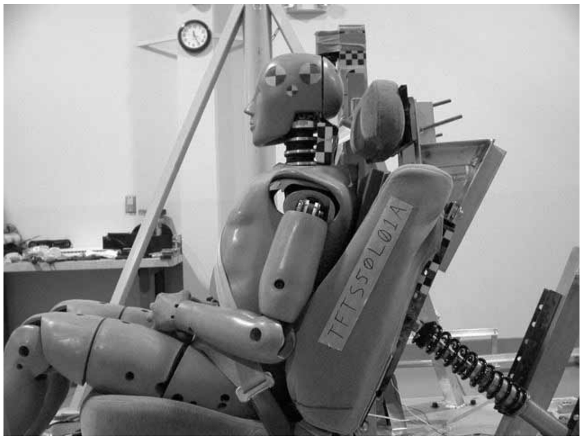


Figure 1. Modified production seat providing adjustable recliner stiffness and head restraint position.

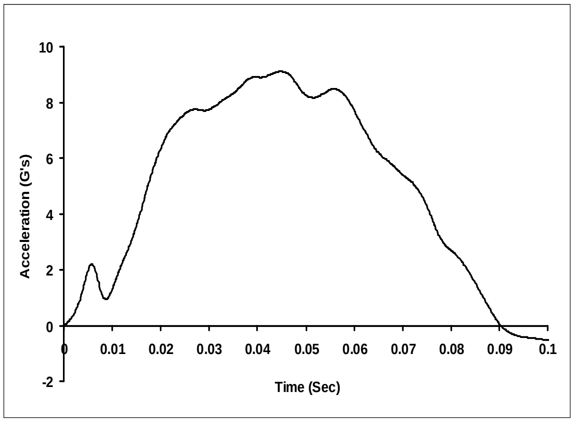


Figure 2. Sled pulse used for rear impact testing based on FMVSS 202 dynamic testing corridor.

Load bolts were mounted at the attachment between the spring assemblies and seatback to verify that the seatback was being loaded symmetrically by the dummy. Seatback rotation was measured using MHD angular rate sensors and/or a string potentiometer. The seatback angle was initially set at 25 degrees relative to vertical, and the head restraint height was set at either 750 mm or 800 mm. The backset was kept constant at 50 mm for all tests. Head restraint height is the distance from the H-point to the top of the head restraint measured parallel to the torso line, as prescribed in FMVSS 202. Backset is defined as the horizontal distance between the posterior aspect of the head and the front surface of the head restraint. This distance was measured using the Head Restraint Measurement Device (HRMD) developed by the Insurance Corporation of British Columbia (ICBC).

The Hybrid III 50M dummy was instrumented with a 9-accelerometer array and a 3-axis array of MHD angular rate sensors in the head, 6-axis upper and lower neck load cells, two 3-axis accelerometers and a 3-axis MHD angular rate sensor in the chest, and a 3-axis lumbar load cell. All sensor data were collected using an on-board TDAS-Pro data acquisition system. In addition to the sensor output, dummy kinematics was recorded for each test using an on-board IMC Phantom 4 digital video camera operating at 1000 frames per second. Aluminum foil sheets were attached to the posterior surface of the head and front surface of the head restraint to serve as a switch to determine head contact times.

Several different series of tests were conducted in which the recliner stiffness was varied from a baseline value of 35 Nm/deg up to a rigid seatback configuration. Tests were typically run at recliner stiffness values of 35 Nm/deg (100%), 70 Nm/deg (200%), 105 Nm/deg (300%), 175 Nm/deg (500%), and rigid. For the first two series of tests, the 300% recliner stiffness was not tested. The baseline recliner stiffness value of 35 Nm/deg represents a relatively compliant single recliner automotive seat [15].

The various series of tests were conducted to evaluate the effects of different seatback and head restraint properties on the head-neck response of the dummy. Table 1 shows the various test series and a brief description of the test configuration.

Table 1. Test configurations for sled tests.

TEST SERIES	CONFIGURATION
RI50H	mid-sized male dummy, FMVSS 202 pulse, 800mm head restraint height, modified Camry head restraint
RI50L	mid-sized male dummy, FMVSS 202 pulse, 750mm head restraint height, modified Camry head restraint
RI50HQ	mid-sized male dummy, FMVSS 202 pulse, 800mm head restraint height, modified Quest head restraint
RI50LQ	mid-sized male dummy, FMVSS 202 pulse, 750mm head restraint height, modified Quest head restraint
RIFOAM	mid-sized male dummy, FMVSS 202 pulse, 750mm head restraint height, modified Quest head restraint, various seatback cushion foam stiffness values

RESULTS

Although the specific mechanisms of whiplash injuries are not completely understood, most researchers agree that these injuries are related to the relative motion between the head and neck. As a preliminary attempt to assess the relative risk of injury as a function of seatback and head restraint properties, the rotations of the head relative to the torso will be analyzed. The primary source of this rotation data is the MHD angular rate sensors attached to the head and upper spine. Video data was used to verify the accuracy of the MHD sensors, and was found to agree within 3 degrees for all tests [16]. Force and moment data obtained from the upper and lower neck load cells is also presented for comparison. Calculations of the various proposed injury criteria discussed above will also be presented, although there is currently no consensus on the threshold levels related to minor whiplash injuries.

Two tests were typically conducted for each test configuration. Results from the repeat tests were found to be fairly consistent, with measured rotations of the seat and dummy generally within 3 degrees over the time period of interest. Figure 3 shows the repeatability of the measured seatback rotation for various recliner stiffness values. The pairing of duplicate test configurations is readily apparent, with the baseline seatback rotations reaching a maximum value of approximately 24 degrees at a time of 150 msec after impact. For the 500% recliner stiffness, the maximum seatback rotation was approximately 10 degrees at 110 msec after impact.

Figure 4 shows the repeatability of the measured head rotation for various recliner stiffness values. Once again, the pairing of duplicate test configurations is readily apparent, with the baseline head rotations reaching a maximum value of approximately 40 degrees at a time of 130 msec after impact. For the rigid seatback configuration, the maximum head rotation was approximately 16 degrees at 85 msec after impact.

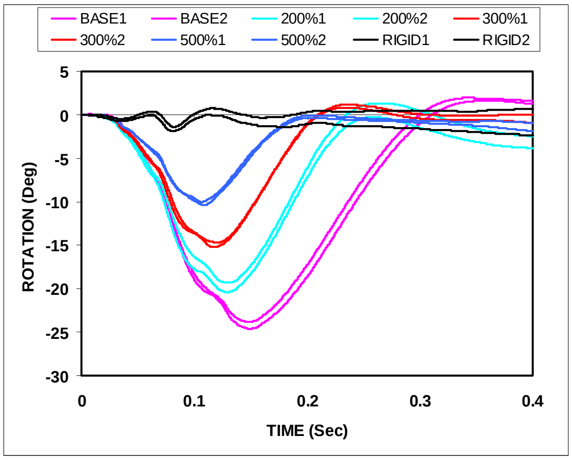


Figure 3. Repeatability of seatback rotation measurements for various recliner stiffness values.

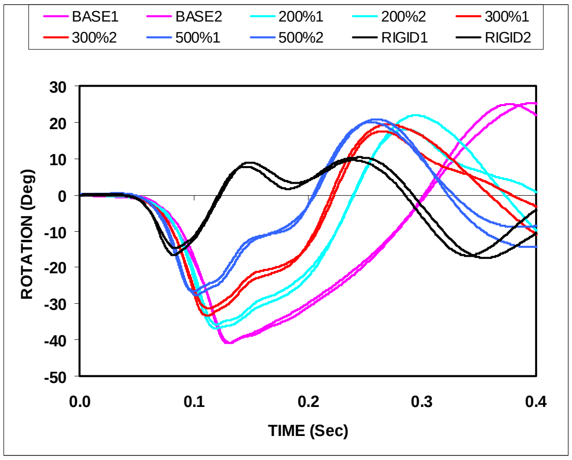


Figure 4. Repeatability of head rotation measurements for various recliner stiffness values.

Measured forces and moments were also found to be fairly consistent for both the upper and lower neck load cells. Shear forces were generally within 30 N for all test configurations. Axial forces were generally within 120 N for recliner stiffness values ranging from baseline to 500%. Measured axial forces for the rigid seatback configuration were somewhat less repeatable, varying by as much as 374 N. Moments about the lateral axis were found to be relatively consistent, with variations generally within 2 Nm for the upper neck load cell and 6 Nm for the lower neck load cell. Figure 5 shows the repeatability of the measured lower neck flexion-extension moments for various recliner stiffness values.

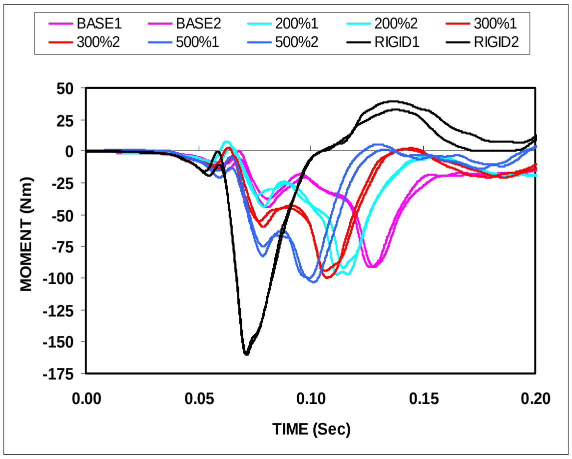


Figure 5. Repeatability of lower neck flexion-extension moment for various recliner stiffness values.

Effects of Recliner Stiffness and Head Restraint Height

Figure 6 shows the effect of recliner stiffness on the rearward rotation of the seatback for test series RI50H and RI50L. As expected, the maximum angle of rotation decreased as the recliner stiffness increased. For the 100% baseline case, the seatback rotated rearward 23 degrees for the mid-sized (50M) dummy at both head restraint heights. Seatback rotation was approximately 8.5 degrees for the 500% recliner stiffness, and was zero for the rigid seatback configuration. [Note: Values presented in bar charts represent the average of all tests conducted for each configuration.]

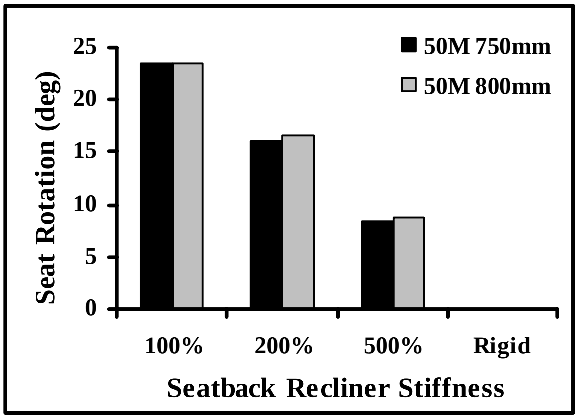


Figure 6. Effect of seatback recliner stiffness on rearward seatback rotation.

Figure 7 shows the effect of seatback recliner stiffness on the maximum rearward (extension) rotation of the head relative to the ground. This head rotation was found to decrease as the recliner stiffness increased for all head restraint configurations. For the 50M dummy, the head rotation decreased from 47 to 26 degrees for the 800 mm height and from 51 to 28 degrees for the 750 mm height.

Similar to the head rotation, the chest rotation relative to ground was also shown to decrease as the recliner stiffness increased for all head restraint configurations, as shown in Figure 8. For the 50M dummy, the chest rotation decreased from 33 to 3 degrees for the 800 mm height and from 34 to 7 degrees for the 750 mm height. In the rigid tests, the chest rotation is primarily associated with compression of the seatback cushion.

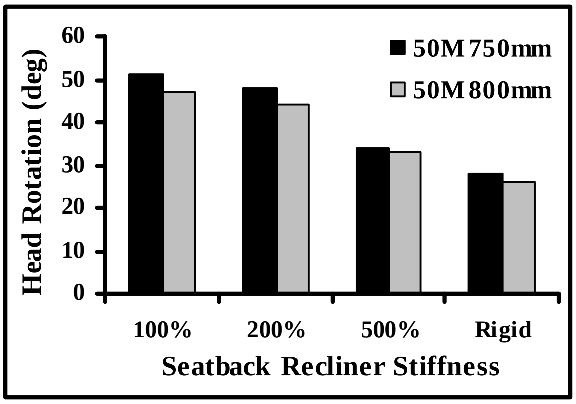


Figure 7. Effect of seatback recliner stiffness on maximum head rotation.

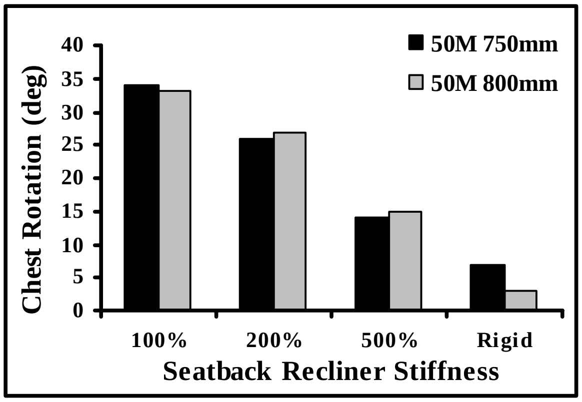


Figure 8. Effect of seatback recliner stiffness on chest rotation.

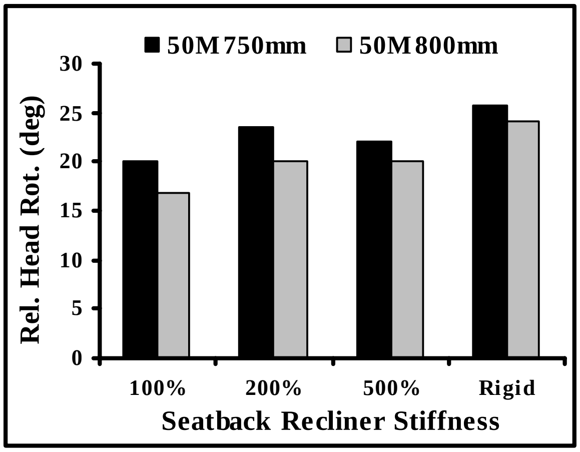


Figure 9. Effect of seatback recliner stiffness on maximum head rotation relative to torso.

Unlike the trends for the individual head and chest rotations relative to ground, the head rotation relative to the chest (Figure 9) did not show a clear trend with respect to recliner stiffness. In general, the relative head rotation increased as the recliner stiffness increased, but this was not a monotonic relationship. For the 50M dummy, the head rotation increased from 17 to 24 degrees for the 800 mm height and from 20 to 26 degrees for the 750 mm height.

One factor affecting the relative head rotation is the amount of time required for the head to make initial contact with the head restraint. As shown in Figure 10, the initial contact time between the head and head restraint decreased as the seatback stiffness increased. For the 50M dummy, the initial contact time decreased from 110 to 52 msec for the 800 mm height and from 106 to 55 msec for the 750 mm height.

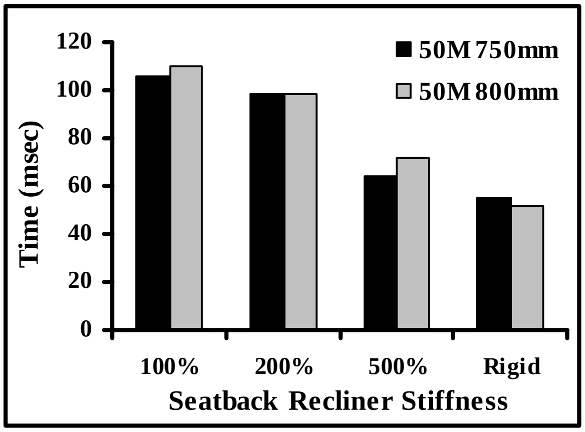


Figure 10. Effect of seatback recliner stiffness on initial head contact time.

Forces and moments recorded by the upper neck load cell were also found to vary with seatback stiffness. Peak values for neck shear force (F_x), tensile force (F_z), and extension moment (M_y) all increased from the baseline case to the rigid case, although they did not show a monotonically increasing trend. Figures 11-13 show the effects of recliner stiffness on upper neck forces and moments. Figure 14 shows the effect of recliner stiffness on the lower neck moment calculated at the T1 vertebra. This lower neck moment was found to increase as the recliner stiffness increased. For the 50M dummy, the lower neck moment increased from 60 Nm to 98 Nm for the 800 mm height and from 67 Nm to 99 Nm for the 750 mm height.

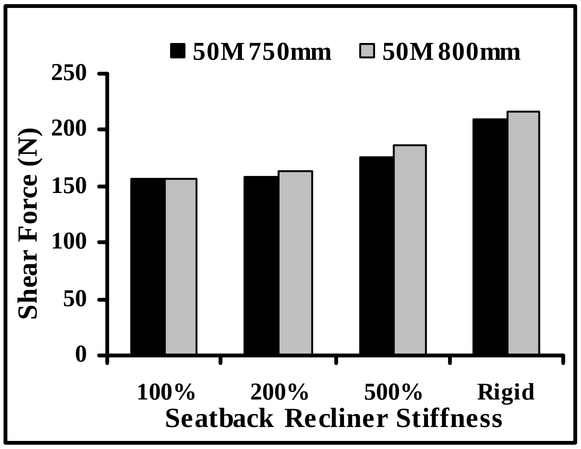


Figure 11. Effect of seatback recliner stiffness on upper neck shear force (Fx).

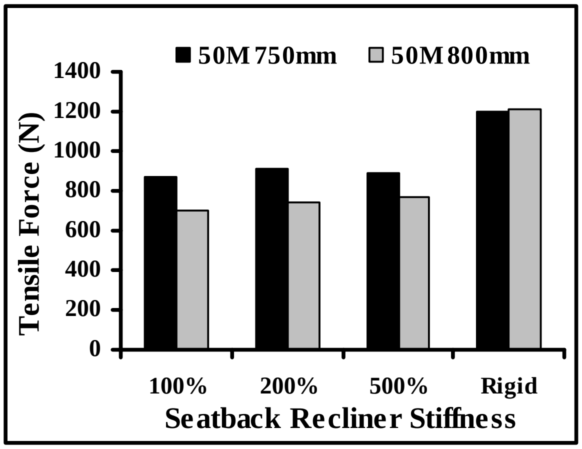


Figure 12. Effect of seatback recliner stiffness on upper neck tensile force (Fz).

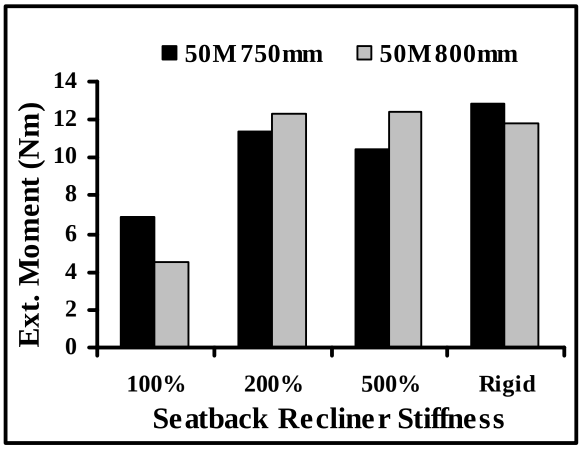


Figure 13. Effect of seatback recliner stiffness on upper neck extension moment (My).

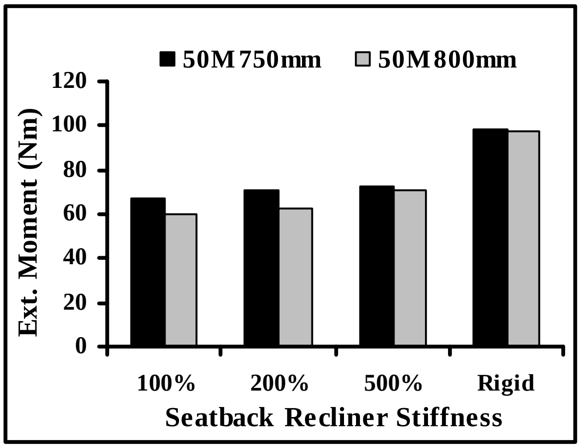


Figure 14. Effect of seatback recliner stiffness on lower neck extension moment (My).

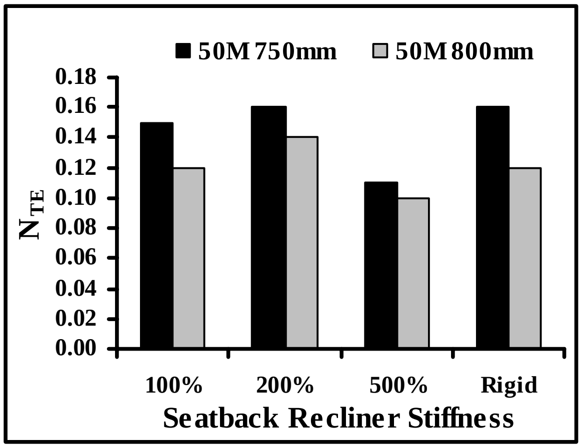


Figure 15. Effect of seatback stiffness on N_{TE} tension-extension neck injury criterion.

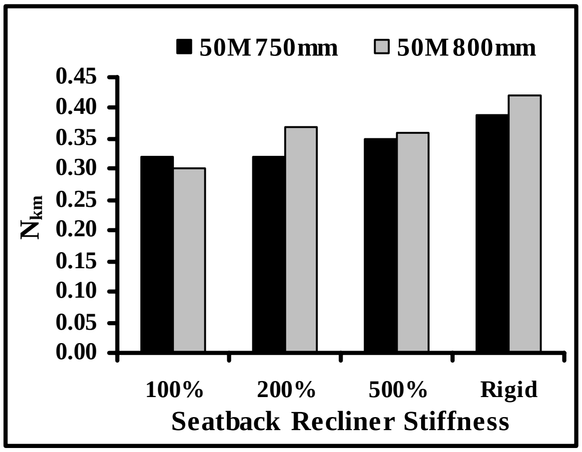
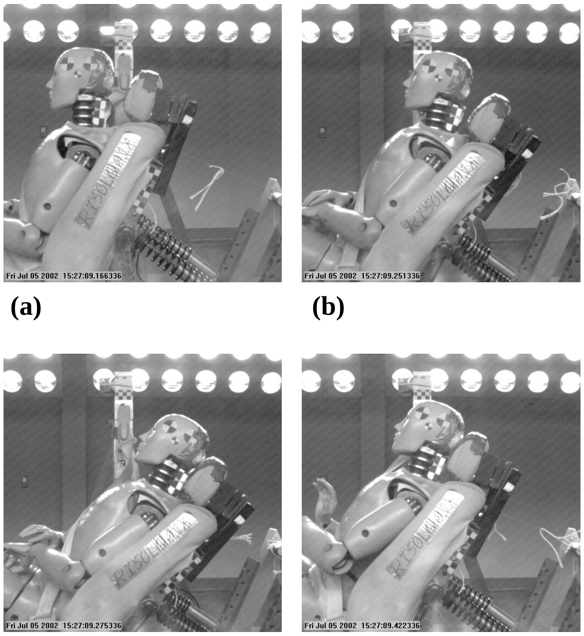


Figure 16. Effect of seatback stiffness on N_{km} shear-moment neck injury criteria.

The Nij neck injury criteria combines the effects of forces and moments acting in the sagittal plane to produce a single value representing the relative risk of neck injury. Although these criteria are normalized to predict serious neck injuries, the Nij values can be used to assess the relative risk of injury. As seen in Figure 15, all of the N_{TE} values are less than or equal to 0.2, which suggests that there is a relatively low risk of sustaining a serious neck injury under these impact conditions.

The N_{km} neck injury criteria combines the effects of shear force and moments acting in the sagittal plane to produce a single value representing the relative risk of neck injury. Unlike the N_{ij} criteria, the N_{km} normalization limits are intended to predict the threshold below which no injury will occur [12]. As seen in Figure 16, all of the N_{km} values are less than or equal to 0.4, which suggests that there is a relatively low risk of sustaining any neck injury under these impact conditions. Results indicated a slight increase in N_{km} as the recliner stiffness increased.

Figure 17 shows a typical kinematic response of a 50M dummy to a nominally 17 kph rear impact sled test with a baseline seatback recliner stiffness of 35 Nm/deg. Figure 17a shows the initial position of the dummy at the moment of impact, with a head restraint height of 750 mm and a backset of 50 mm. As the dummy begins to move rearward, the lower torso compresses the lower portion of the seatback, causing it to rotate rearward (Figure 17b). As the dummy moves horizontally rearward, the seatback rotates downward, giving the appearance that the dummy is moving upward. Review of the high-speed video data suggests that the head and upper torso do not move upward relative to ground. The pelvis, however, does move upward and comes slightly off the seat bottom, but is reasonably well restrained by the lap portion of the seatbelt. The torso does show "ramping" under these test conditions, but it is important to recognize that the upward motion of the torso is only seen relative to the seatback, and not to ground.



(a) **(b)**

(c) **(d)**

Figure 17. Sequence of events for rear impact sled tests. (a) initial position at impact, (b) apparent ramping of dummy relative to seatback, (c) head contact, and (d) rebound of seatback and torso.

The upper torso begins to rotate downward, with the head making initial contact with the head restraint at approximately 110 msec (Figure 17c). The seatback and torso continue to rotate downward together for approximately another 40 msec before the seatback begins to rotate forward and the torso begins to rebound off the seatback (Figure 17d). The timing of the sequence of events will depend greatly on the type of dummy and seatback recliner stiffness.

Effects of Head Restraint Design

Analysis of the data from the first two test series revealed that a significant amount of head rotation was occurring after initial contact between the head and head restraint. This finding led us to conduct the next two series of tests to evaluate the effects of head restraint design. For these tests, the original modified 1999 Toyota Camry head restraint, which was attached to the seatback through the normal vertical support posts, was replaced by a modified 1997 Nissan Quest head restraint that was attached rigidly to the seat frame reinforcements. Once again, the head restraint attachment was modified to provide adjustability of the height and backset. The Nissan Quest head restraint was selected because it has a more robust design with a thinner layer of comfort foam on the front and top surfaces. Tests were conducted with the mid-sized male (50M) Hybrid III dummy with two different head restraint heights and five different recliner stiffness values. Figures 18 and 19 show the effect of head restraint design on the rotation of the head relative to the torso for a head restraint height of 800 mm and 750 mm, respectively.

As discussed above, the rotation of the head relative to the torso generally increased as the recliner stiffness increased. This general trend holds for both head restraint designs. However, Figures 18 and 19 clearly indicate that the amount of relative head rotation is significantly less for the tests with the modified Quest head restraint that was rigidly attached to the seat frame. The relative head rotations were roughly half for the Quest head restraint, with the actual reductions ranging from approximately 40-60 percent less. This reduction in relative head rotation was primarily influenced by the amount of head rotation occurring after initial contact with the head restraint.

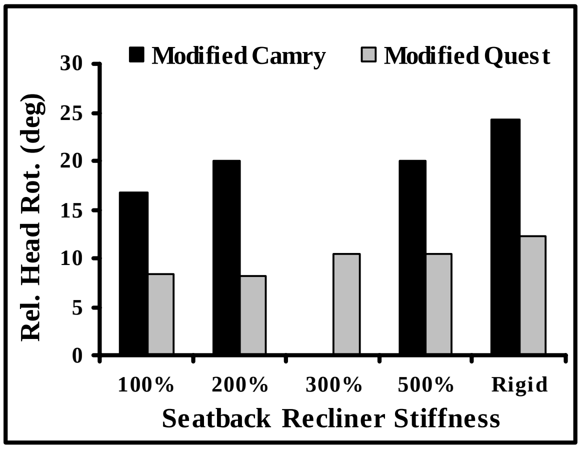


Figure 18. Effect of head restraint design on maximum relative head rotation for an 800 mm head restraint height.

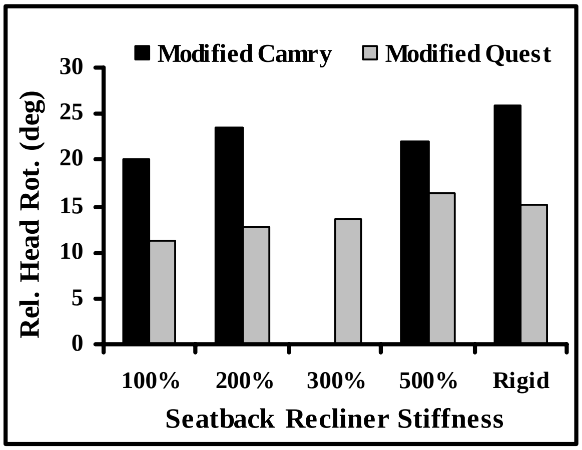


Figure 19. Effect of head restraint design on maximum relative head rotation for a 750 mm head restraint height.

Figures 20-22 show the effects of seatback recliner stiffness on upper neck forces and moments for the modified Quest head restraint. These results can be compared with the forces and moments presented in Figures 11-13 for the modified Camry head restraint. The stiffer modified Quest head restraint did not change the general trends observed with the more compliant modified Camry head restraint. However, the maximum values of the shear forces and extension moments showed a significant decrease. The amount of decrease varied with the head restraint height and recliner stiffness level. Maximum values for the tension force showed little change between the different head restraint designs.

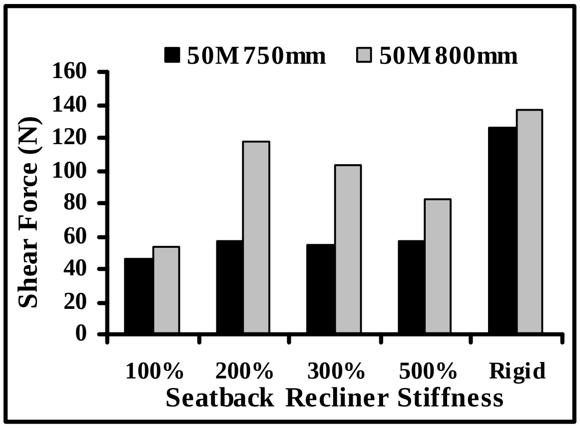


Figure 20. Effect of seatback recliner stiffness on upper neck shear force (Fx) for modified Quest head restraint.

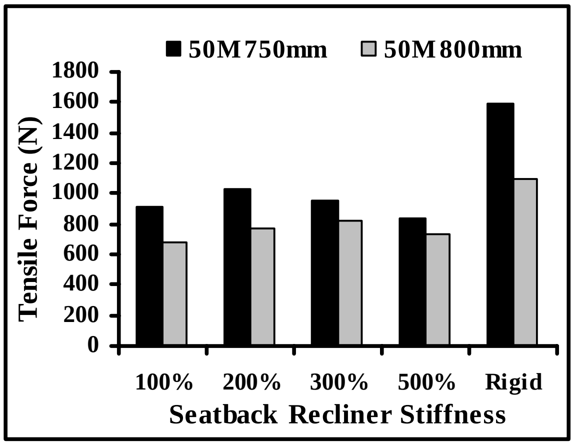


Figure 21. Effect of seatback recliner stiffness on upper neck tensile force (Fz) for modified Quest head restraint.

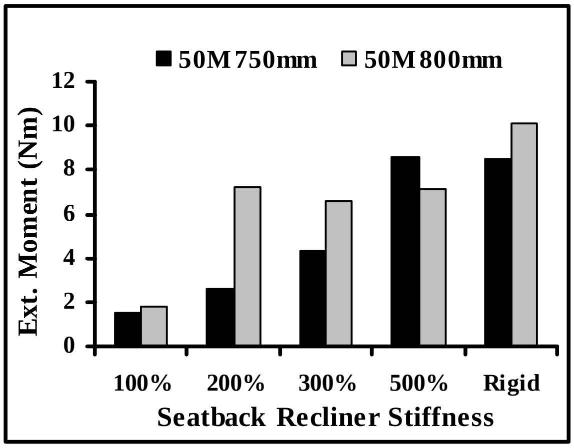


Figure 22. Effect of seatback recliner stiffness on upper neck extension moment (My) for modified Quest head restraint.

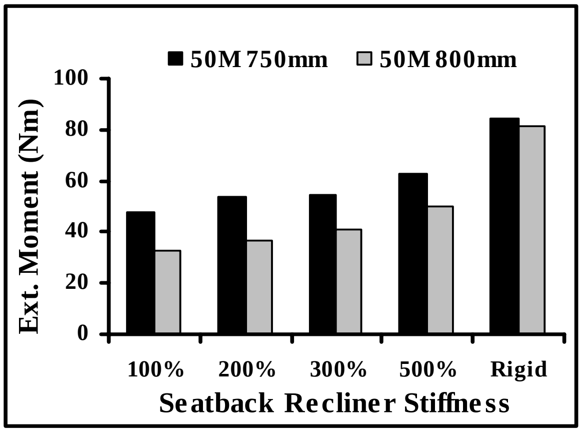


Figure 23. Effect of seatback recliner stiffness on lower neck extension moment.

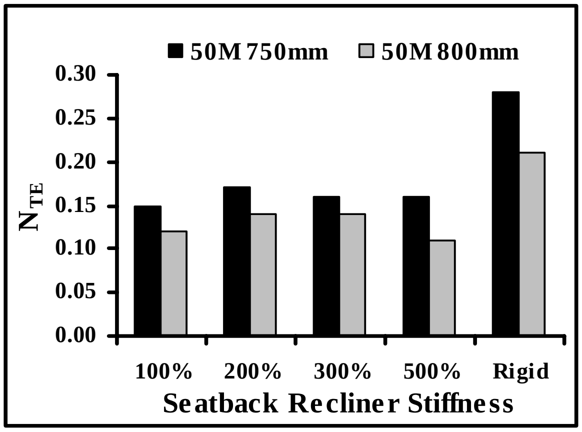


Figure 24. Effect of seatback stiffness on N_{TE} tension-extension neck injury criterion for modified Quest head restraint.

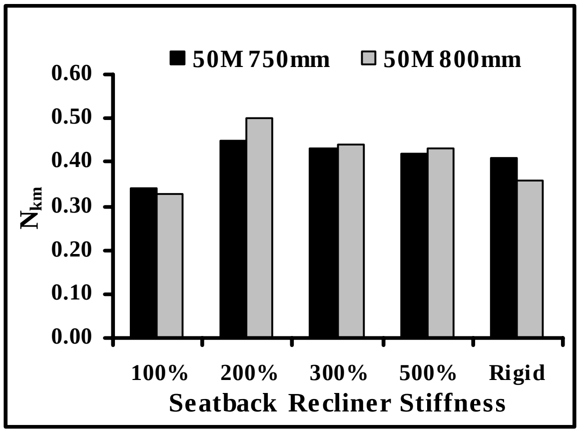


Figure 25. Effect of seatback stiffness on N_{km} shear-moment neck injury criteria for modified Quest head restraint.

Figure 23 shows the effect of recliner stiffness on lower neck moments for the modified Quest head restraint. These results can be compared with the lower neck moments presented in Figure 14 for the modified Camry head restraint. The stiffer Quest head restraint does not change the general trend observed with the more compliant modified Camry head restraint. However, the maximum values of the lower neck moments decrease by an average of 20 percent.

Figures 24 and 25 show the calculations for Nij and Nkm, respectively, for the modified Quest head restraint. These figures can be compared with Figures 15 and 16, respectively. As stated above, the maximum values for these proposed injury criteria are relatively low, suggesting a relatively low risk of neck injury associated with these impact conditions

Effects of Seatback Cushion Stiffness

Another seat design parameter that affects occupant response during a rear impact is the stiffness of the seatback cushion, which is controlled by the stiffness of the foam and also any structural cross-members within the seatback support frame. This design parameter was investigated by adding 2 inches (51 mm) of polyurethane foam of various stiffness values to the front surface of the seatback. The dummy and head restraint were repositioned to maintain the proper head restraint height and backset values.

Three different grades of polyurethane foam were tested with the 50M Hybrid III dummy, all at the FMVSS 202 dynamic sled pulse with a 750 mm head restraint height. The foams are referred to as grades 1, 2, and 3, with grade 1 having the lowest stiffness and grade 3 having the highest stiffness. Force-deflection properties of the three foams are shown in Table 2.

Table 2. Force-deflection properties of the foams added to the front of the seatback.

Foam Grade	1	2	3
Density (kg/m^3)	45	45	59
Pressure Load (kPa) (at 25% compression)	2.4	4.8	6.2

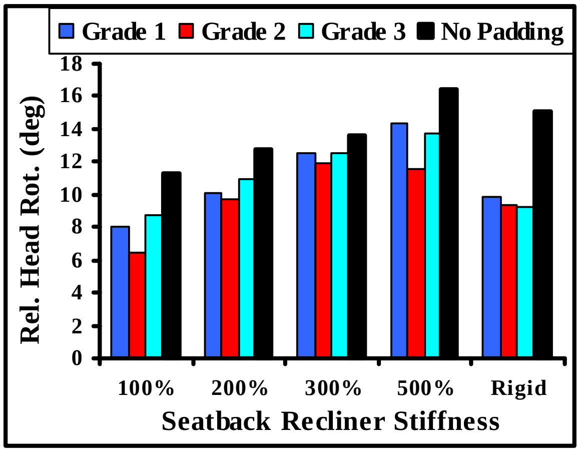


Figure 26. Effect of seatback cushion stiffness on maximum head rotation relative to torso.

Figure 26 shows the effect of seatback cushion stiffness on the rotation of the head relative to the torso. For all recliner stiffness levels, the added foam reduced the amount of head rotation as compared with the original seatback upholstery. The amount of reduction in head rotation ranged from 1 to 6 degrees, and varied with the grade of foam and recliner stiffness. For all recliner stiffness values, except the rigid seat configuration, the grade 2 foam resulted in the greatest reduction in relative head rotation. Load cell data was not collected for this series of tests.

DISCUSSION

In the absence of a consensus on the specific mechanisms of rear impact whiplash injuries, we have analyzed the test data under the assumption that the forces and moments acting on the neck, and the relative rotations between the head and torso, are related to the risk of neck injury. Although this assumption seems reasonable from a biomechanics perspective, the determination of the specific relationship between these factors and the probability of neck injury will require further research. Relative translation between the head and torso is most likely also related to whiplash injury, but is difficult to measure without requiring video analysis.

As expected, the rearward rotation of the seatback decreased as the seatback stiffness increased, as shown in Figures 3 and 6. Additionally, the seatback rotation is not significantly affected by adjustment of the head restraint height. For the Hybrid III 50M dummy, the seatback rotation varied by less than 1 degree for the tests conducted at the 750 mm height as compared with the corresponding tests at the 800 mm height.

Initial head contact time was shown to be largely dependent on seatback stiffness, as shown in Figure 10. Head restraint height did not have a significant impact on head contact time. Additionally, the head restraint design (modified Camry vs. Quest) did not have a significant effect on the head contact time nor the amount of head rotation at the moment of initial head contact. Head contact times varied by no more than 7 msec, and head rotations at initial contact varied by no more than 3 degrees, for all similar configurations with the different head restraint designs. This result was expected since the position of the head restraint relative to the head was unchanged between the different configurations at the same head restraint height.

The maximum head and chest rotations were clearly affected by the amount of seatback rotation. As the seatback stiffness increased, the amount of seatback rotation decreased, resulting in a decrease in both the maximum head and chest rotations relative to ground. Maximum head rotation decreased on average by 22 degrees between the baseline and rigid cases (Figure 7). Maximum chest rotation decreased on average by 29 degrees between the baseline and rigid cases (Figure 8). The rotation of the head relative to the chest was found to increase as the seatback stiffness increased. The maximum head rotation relative to the torso increased on average by 6 degrees between the baseline and rigid cases (Figure 9).

It is important to recognize that the seat used for this study was not a production seat, but was modified to make the seat stronger and more durable. Steel channel was welded to the U-shaped frame of the original seat structure to provide attachment points for the spring-damper assemblies, MHD angular rate sensors, and a string potentiometer. A sheet metal pan was welded across the rear of the seatback, effectively removing the original spring and support bracing within the seatback. The original foam and upholstery was left intact on the front surface of the seatback. The seat bottom was not modified for these tests.

As a result of the modifications to the seatback, the interaction of the dummy with the seatback will most likely be different than with an unmodified production seat. Additionally, the Hybrid III dummy is expected to interact with the seat differently than a human occupant during a rear impact collision. Although other existing dummies (THOR, BIORID, and RID 2) may possess a more biofidelic response in rear impact, the Hybrid III dummy was used for this test series because it is the only dummy currently approved for use in FMVSS Part 572. The objective of this study was not to evaluate any particular seat or dummy design, but rather to compare the occupant response relative to certain head restraint and seatback design parameters.

Aside from the relative rotation between the head and torso, the forces and moments acting in the neck are believed to be related to the risk of whiplash injury. In the sagittal plane, the neck loads that are most critical for evaluating rear impact whiplash injury risk are the shear force (Fx), tensile force (Fz), and extension moment (My). As shown in Figures 11-14 and 20-23, each of these parameters generally increased as the seatback recliner stiffness increased. Maximum values for the baseline cases were consistently lower than for the rigid cases, but the trends were not monotonically increasing. The maximum shear and tensile forces recorded at the upper neck for all test conditions were 216 N and 1595 N, respectively. The maximum extension moment recorded at the upper neck for all test conditions was 12.0 Nm. All of these maximum values are well below the established thresholds for serious injury, indicating that these test conditions would not be expected to produce any serious AIS $\geq$ 3 neck injuries.

Figure 27 presents typical data collected from both load cells, along with a plot of the relative head-to-torso rotation. The upper neck moment exhibits an oscillatory response beginning around 40 msec, with the maximum extension moment occurring at approximately 150 msec. The lower neck moment exhibits a more obvious extension peak at approximately 130 msec, which corresponds with the time of maximum relative head rotation. The maximum values for the Nij and Nkm neck injury criteria occur at approximately 120 msec, which is slightly prior to the maximum relative head rotation.

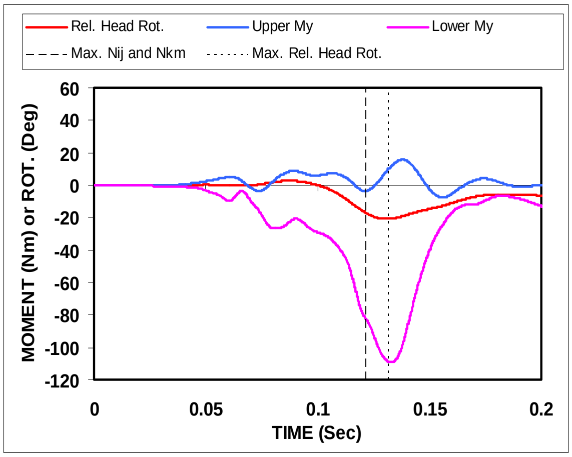


Figure 27. Comparison of upper and lower neck extension moment data.

The maximum value for the N_{TE} neck injury criterion was 0.28, as shown in Figures 15 and 24, which suggests that these test conditions would not result in any serious neck injuries. Similarly, the maximum values for the Nkm neck injury criteria was 0.50, as shown in Figures 16 and 25, which would further suggest that these test conditions are unlikely to produce any significant neck injuries.

Head restraint design was found to have a significant effect on the maximum relative head rotation, and also the forces and moments acting in the neck. Although head rotations at the time of initial contact with the head restraint were found to be reasonably consistent between the two different head restraint designs, the maximum relative head rotations varied by up to 12 degrees for the 800 mm head restraint height and 11 degrees for the 750 mm height. These differences are related to the amount of rearward rotation of the head restraint relative to the seatback, which was essentially zero for the rigidly attached Quest head restraint. Upper neck forces and moments were also found to vary significantly with head restraint design. Shear forces and extension moments decreased significantly with the rigidly attached Quest head restraint, while little change was observed for the tensile forces. Lower neck extension moment decreased by up to 27 Nm for the 800 mm head restraint height and 19 Nm for the 750 mm height.

Prior to the selection of the Nissan Quest head restraint for evaluation in this study, a survey of head restraint designs revealed a wide variety of structural and aesthetic designs. Some head restraints provided minimal structural support, and consisted primarily of a U-shaped metal tube with two vertical posts that inserted into sleeves in the top of the seatback. The main portion of the head restraint consisted of little more than a thick block of relatively soft comfort foam. Other head restraint designs included a plastic core attached to the U-shaped tube, which provided some internal support behind the comfort foam. These head restraints typically had thick layers of soft foam in the areas of potential head contact, namely on the front and top surfaces. The Quest head restraint consisted of a metal core welded to the U-shaped tube. This metal core extended vertically higher than the plastic cores previously observed, and the foam thickness at the front and top of the head restraint was less than 20 mm. This more robust internal structure, combined with the rigid attachment to the seat frame, provided a greater amount of support to the dummy head during rear impact testing.

Another important design parameter related to head restraints is the contouring or shaping of the overall head restraint. Due to the procedure in FMVSS 202 for measuring the height of a head restraint, the point where the height is measured may be toward the back surface of the head restraint, which is often not the location of head contact. Variations in contour can change the "effective height" of the head restraint, and may alter the location of contact with the dummy's head.

As shown in Figure 26, the addition of padding to the front surface of the seatback reduces the rotation of the head relative to the torso. The primary reason for this is that the dummy's torso is able to penetrate deeper into the seatback before engaging the structural cross-members within the seat frame. This effectively reduces the backset of the head restraint and improves the timing between the rearward motion and forward rebound of the head and torso. Although the grade 2 foam appeared to perform the best for a mid-sized male Hybrid III dummy under an FMVSS 202 dynamic crash pulse, an optimal seat design should also consider other foam thickesses, occupant sizes, and crash pulses.

CONCLUSION

This series of tests demonstrates that the head/neck response of an occupant to a rear impact collision depends on a number of seat design parameters. The parameters evaluated in this experimental study included head restraint height, head restraint design, seatback cushion stiffness, and seatback recliner stiffness. Other potential factors that will be evaluated in future testing include occupant size, head restraint backset, seatback energy return, and impact speed.

Based on the values of the head rotation relative to the chest and the forces and moments acting in the neck, results from this testing suggest that the risk of whiplash injury can not simply be predicted based on seatback stiffness or head restraint position. Occupant response to a rear impact is a dynamic event involving complex interactions between the head and head restraint, and also the torso and seatback. Optimal protection for an occupant should consider the design of the head restraint and seatback as a system, and must recognize that each component will affect the occupant's interaction with the other.

It is important to realize that the modified seat used in this study does not interact with the dummy in the same manner as a production seat. Additionally, the findings from this study are only valid for a nominal impact speed of around 17 kph; future testing will verify these findings at higher speeds and for other occupant sizes.

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