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ABSTRACT

The present study investigated the effects of the structural stiffness of the head restraint and its attachment rigidity on the biomechanical responses and related injury measures of the neck in a rear impact vehicular collision. A series of simulated rear impacts were conducted using a mid-sized male test dummy seated in a modified late-model front passenger seat on a deceleration crash sled with a FMVSS 202 pulse. Preliminary results demonstrated that a more rigid head restraint in its design and attachment produced lesser values in most biomechanical injury measures such as neck shear force, neck extension bending moment, tension-extension neck injury criterion (Nij), shear-moment neck injury criterion (Nkm), and head-torso relative extension angular displacement. This is true for a wide range of seatback recliner stiffness. This suggests that a more rigid head restraint may have a protective advantage over a more pliant one for the neck in a rear impact. The result of this study underscores the need for dynamic testing to completely evaluate the performance of head restraint system.

INTRODUCTION

Although typically classified as AIS 1 minor injuries, whiplash associated disorders (WAD) of the head and neck resulting from a rear impact motor vehicle collision represent a substantial cost to society, estimated at over $5 billion annually in the United States. Despite years of research by numerous investigators, the specific mechanisms of WAD continue to be a source of debate within the automotive safety community. Nevertheless, most researchers agree that controlling the relative motion between the head and torso will reduce the risk of such disorders in a rear impact collision. Various reports have suggested that a head restraint position that is higher and closer to the occupant's head is associated with a lower rate of WAD (States et al. 1972; Hell et al. 1998; Farmer et al. 1999; Welcher and Szabo 2001). Recent studies have also found that other seat design variables can influence neck injury risks in rear impacts (Linder et al. 2001; Svensson et al. 1998). A number of new seat designs utilize active mechanisms to reduce the relative motion between the head and torso during rear impact (Wiklund and Larson 1998; Jakobsson et al. 2000).

The objective of this study was to investigate the effects of passive structural rigidity in head restraint design and attachment on neck injury risk measures in low speed rear impact crashes. The experimental study was carried out using a deceleration sled and a Hybrid III 50th percentile male dummy.

METHODS

A production automotive front-passenger seat from a 1999 Toyota Camry was modified to allow for wide-range adjustment of seatback recliner stiffness, head restraint height, and backset. The normal recliner mechanism was replaced with a simple pin joint to provide free rotation at the hinge. Seatback reclining 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 of the seatback. To provide a repeatable test system, the seatback frame structure was modified with a sheet metal plate and steel channels to provide attachment points for the spring-damper assemblies.

Tests were conducted on a Via Systems deceleration sled using the Hybrid III mid-sized male (50M) test dummy seated in a rear-facing seat. The head restraint height was set either at 750 mm or 800 mm measured from the seating reference point using an H-point machine in accordance with SAE J826 specifications. The seatback angle was set at 25 degrees relative to vertical. The dummy was positioned in accordance with standard seating procedures as prescribed in the Federal Motor Vehicle Safety Standard (FMVSS) No. 202 NPRM. The seatbelt was fastened and the backset was kept constant at 50 mm for all tests. The test setup is pictured in Figure 1. Rear impact tests were conducted at a velocity change of 17 km/h. A sinusoidal sled pulse was used that fits within the FMVSS No. 202 dynamic testing corridor, with a nominal peak acceleration and duration of 9.0 G's and 90 milliseconds, respectively (Figure 2).

The dummy was instrumented with accelerometers (Endevco 7264-2000) and angular rate sensors (ATA ARS-01S) in the head and chest, upper and lower neck load cells, and a lumbar load cell. All sensor data were collected using an on-board TDAS-Pro data acquisition system and processed according to SAE J211 specifications. The angular rate sensors were filtered and integrated to obtain the angular displacement-time histories (Voo et al. 2003). The time history of the head making contact with the head restraint was recorded by an aluminum foil contact switch. In addition to the sensor data, dummy kinematics was recorded for each test using an on-board IMC Phantom 4 digital video camera operating at 1000 frames per second.

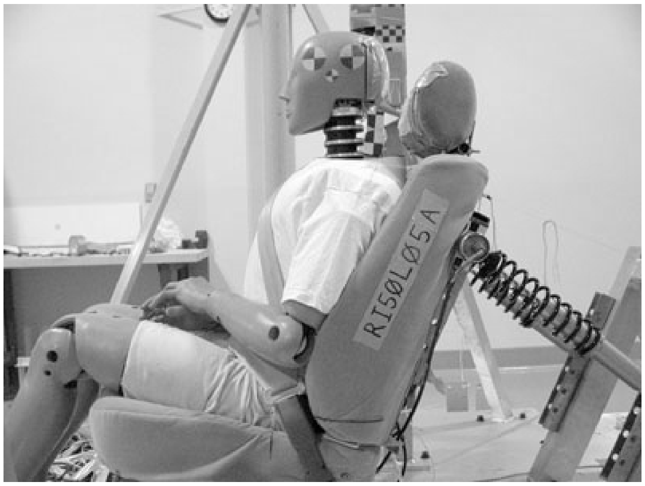

Figure 1. Test setup of a 50th percentile dummy positioned in the test seat on a deceleration sled

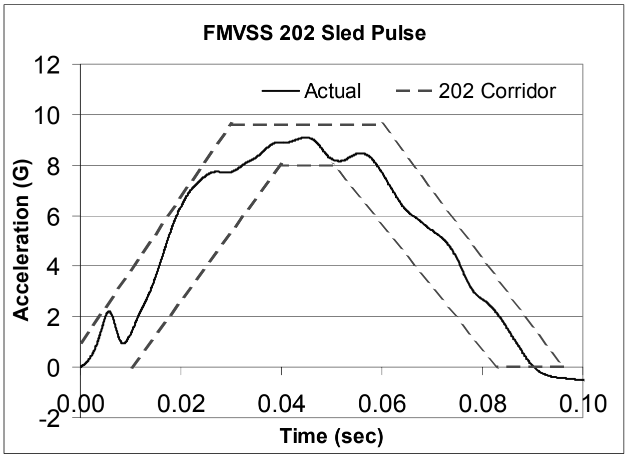

Figure 2. Sled pulse used for rear impact testing based on FMVSS 202 dynamic testing corridor.

Two different types of head restraints were used in the present study. The rigid head restraint (RIGID) was one from a 1997 Nissan Quest minivan and modified for a more rigid attachment to the seatback. Its internal structure included a steel rod welded to an approximately 5-inch-tall stamped sheet metal support covered with an average of 1-inch-thick foam (Figure 3). Three threaded steel rods were welded to this sheet metal support to provide means of rigid attachment. The original foam and fabric cover were retained through the modification. The modified head restraint (RIGID) was bolted onto the steel frame of the seatback using wood blocks and steel channels (Figure 3). The wood blocks provided the adjustment of the backset while the channels provided the height adjustment for the head restraint. The other comparatively pliant head restraint (FLEX) was one from a 1999 Toyota Camry and modified for easy adjustability of height and backset. Its internal structure included a steel rod running through a plastic enclosure that allowed a certain range of relative rotation. This rotation was used to adjust the relative position between the head and head restraint. The head restraint was rotated to the backward extreme before the height and backset were determined. Its mounting structure was modified such that the head restraint could be adjusted vertically and horizontally (Figure 4). The FLEX was mounted directly into the two original post supports on the top of the Camry seatback. The FLEX was therefore much more compliant than the RIGID. Both head restraints had their original upholstery intact during testing.

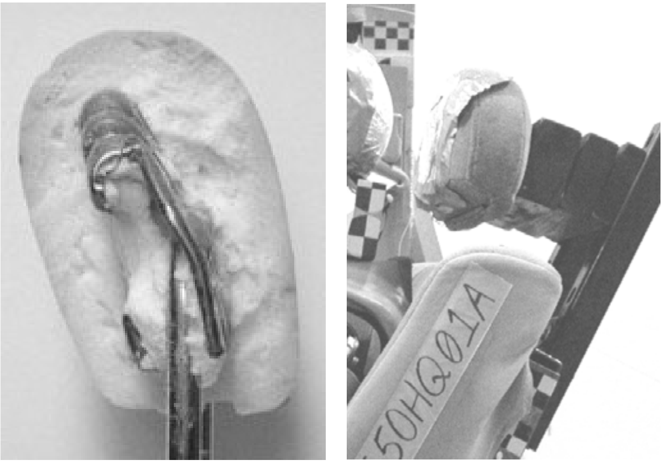

Figure 3. The RIGID head restraint with its internal structure (left) and attachment (right)

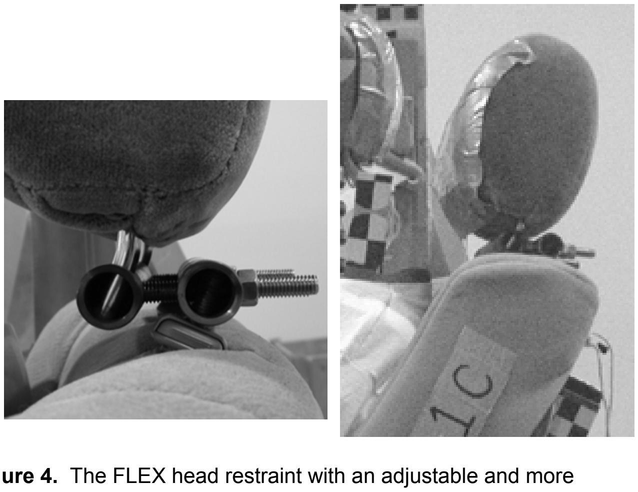

Figure 4. The FLEX head restraint with an adjustable and more flexible attachment

A total of 32 rear impact sled tests were included in this study. The test parameters included two different head restraints, two head restraint heights, and four seat recliner stiffness settings. For both the RIGID and FLEX head restraint the same test matrix was executed (Table 1). Tests were repeated for each configuration.

Table 1. Test matrix for the rear impact sled experiment

Seat Recliner Stiffness	HR Low (750 mm)	HR High (800 mm)
35 (Nm/deg)	2	2
70 (Nm/deg)	2	2
175 (Nm/deg)	2	2
Rigid	2	2

The effects of the two different head restraint structures on whiplash injury risks were evaluated using the following biomechanical quantities: maximum neck shear force (Fx), maximum neck extension moment (My), maximum head extension angular displacement relative to torso (Ry), maximum neck tension-extension injury criterion (Nij) (Kleinberger et al. 1998; Eppinger et al. 2000), and maximum neck shear-extension injury criterion (Nkm) (Schmitt et al. 2001). The maximum values for Fx, My and Ry were determined from their respective time-histories before or during the time when the head made contact with the head restraint (Figure 5). The index Nij included combined effect of tensile force and extension bending moment. Similarly, the index Nkm considers combined effect of posterior shear force and extension bending moment. The time histories of Nij and Nkm were derived from time histories of neck load cell data. Their maximum values were also determined within the time-period before or during head contact with the head restraint. The average of maximum values from two repeat tests for each configuration was used in the comparison analysis.

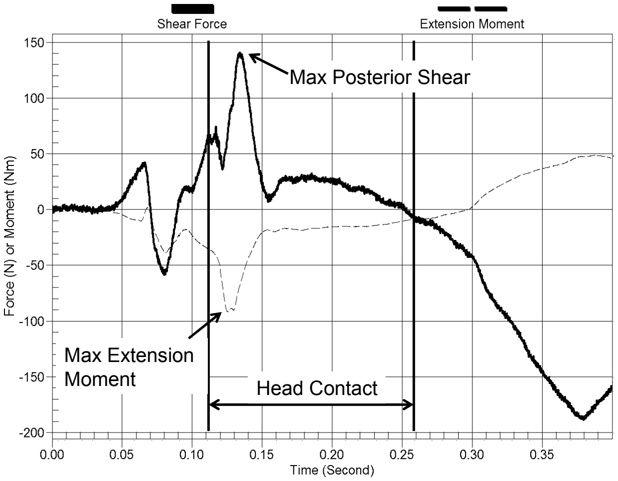

Figure 5. Selecting maximum values for the upper neck posterior shear force Fx and lower neck extension bending Myl

RESULTS

The high-speed video recording revealed that the FLEX head restraint allowed the head to continue to translate and rotate backward beyond the head compression of the head restraint foam layer (Figure 6). In contrast, the RIGID head restraint did not allow the head to move further back beyond the compression of the foam layer.

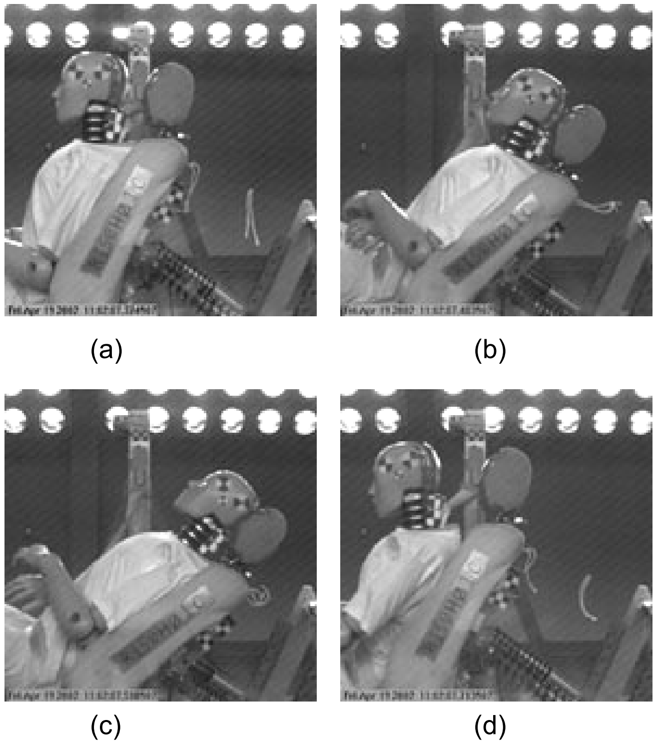

Figure 6. Sequence of events for rear impact sled tests. (a) initial position at impact, (b) start of head contact, (c) head compressing head restraint, and (d) rebound of the seatback and dummy.

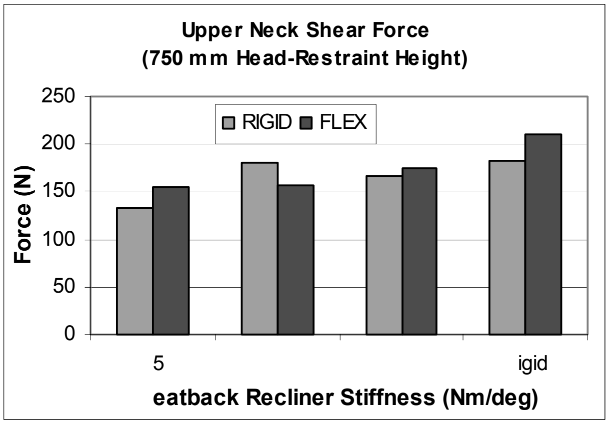

Figure 7a. Maximum upper neck shear force for RIGID and FLEX head restraints at 750 mm height

The upper neck sustained 50% - 70% less shear force (Fx) with the RIGID head restraint than with the FLEX in the higher (800 mm) head restraint (HR) position for all the seat recliner stiffness levels (Figure 7b). No significant difference was observed for the lower (750 mm) HR position (Figure 7a).

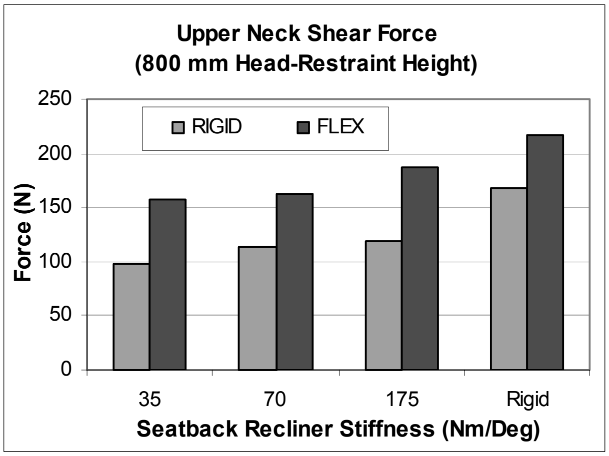

Figure 7b. Maximum upper neck shear force for RIGID and FLEX head restraints at 800 mm height

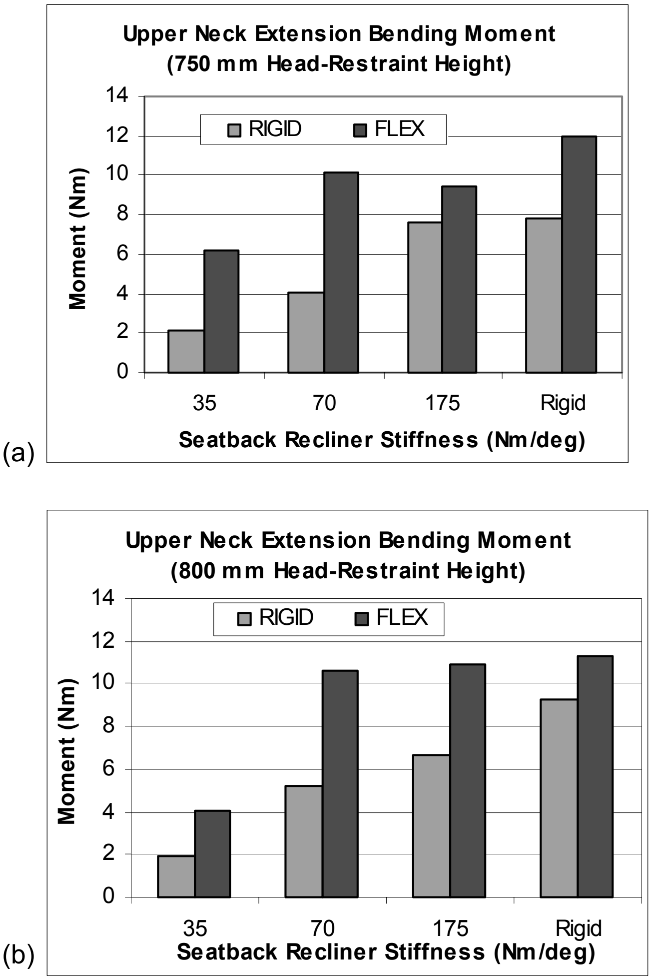

Figure 8. Maximum upper neck extension bending moment for RIGID and FLEX head restraints at 750 mm and 800 mm heights

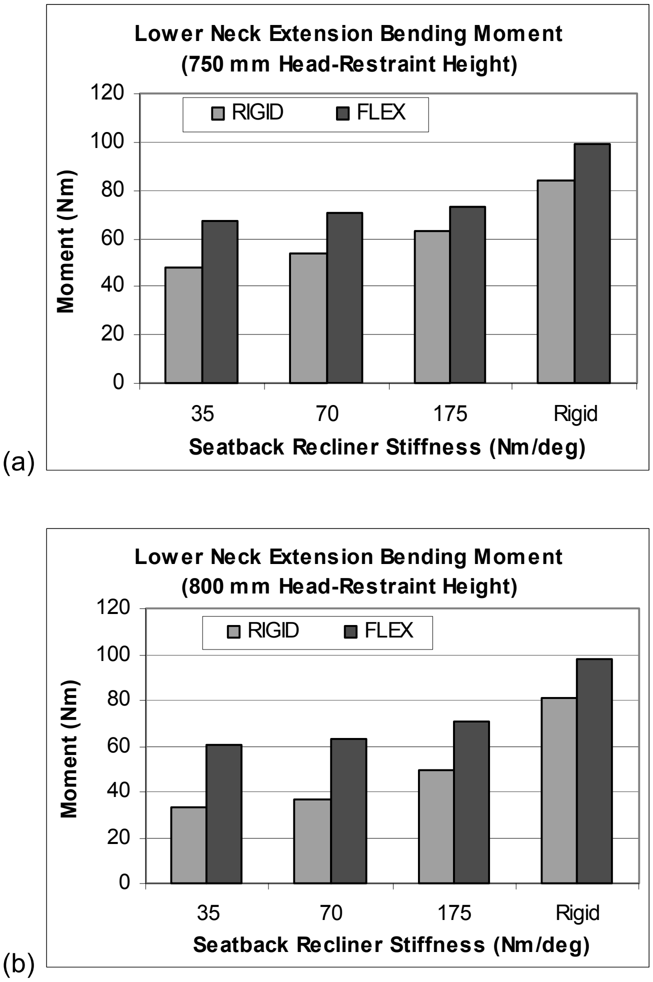

Figure 9. Maximum lower neck extension bending moment for RIGID and FLEX head restraints at 750 mm (a) and 800 mm (b) positions

The upper neck consistently sustained less extension moment My(upper) with the RIGID than with the FLEX in both high and low HR positions (Figures 8a and 8b). The difference ranged from 15% to 60% depending on the seat recliner stiffness levels. The lower neck extension moment My(lower) exhibited similar results (Figures 9a and 9b), ranging from 14% to 42%.

A similar behavior was also observed in the kinematic responses measured by the angular rate sensors. The extension rotations Ry between the head and the torso were consistently less with RIGID than with the FLEX in both HR positions and all the seat recliner stiffness levels (Figures 10a and 10b). The difference ranged from 26% to 59% depending on HR position and seat recliner stiffness level.

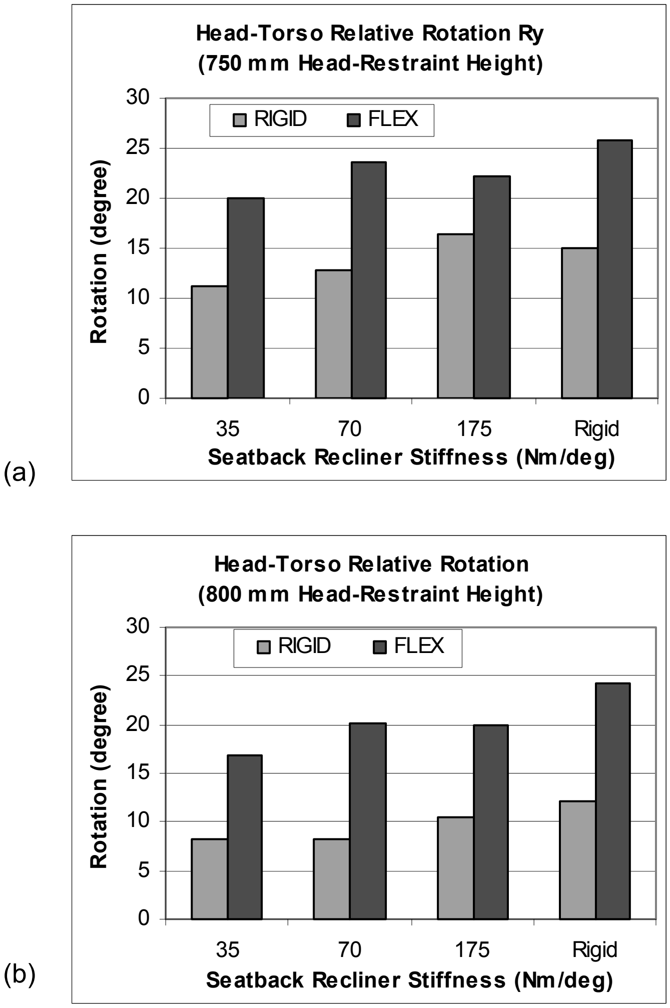

Figure 10. head relative to torso rotation in sagittal plane Ry for RIGID and FLEX head restraints at 750 mm (a) and 800 mm (b) positions

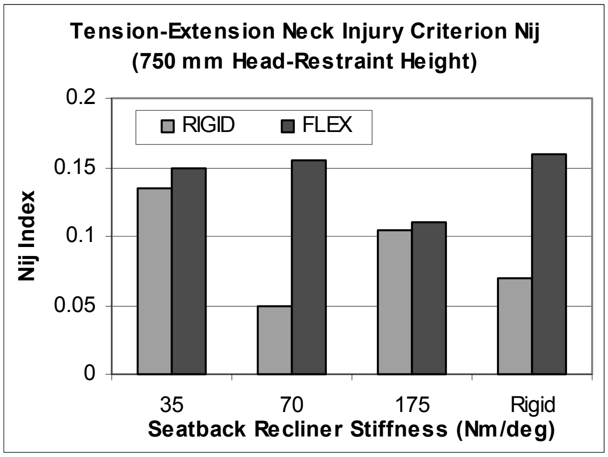

Figure 11a. Maximum tension-extension neck injury criterion Nij for RIGID and FLEX head restraints at 750 mm height

In general, the values of the combined neck injury criteria Nij and Nkm were lower with the RIGID than the FLEX (Figures 11a-12b), but the difference varied considerably from almost 70% in one case to nearly zero in another (Figure 11a).

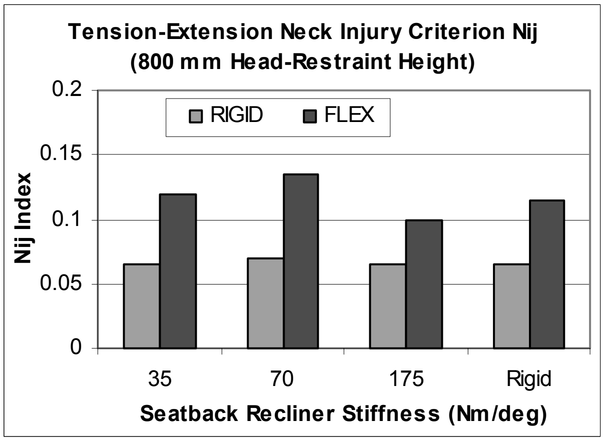

Figure 11b. Maximum tension-extension neck injury criterion Nij for RIGID and FLEX head restraints at 800 mm height

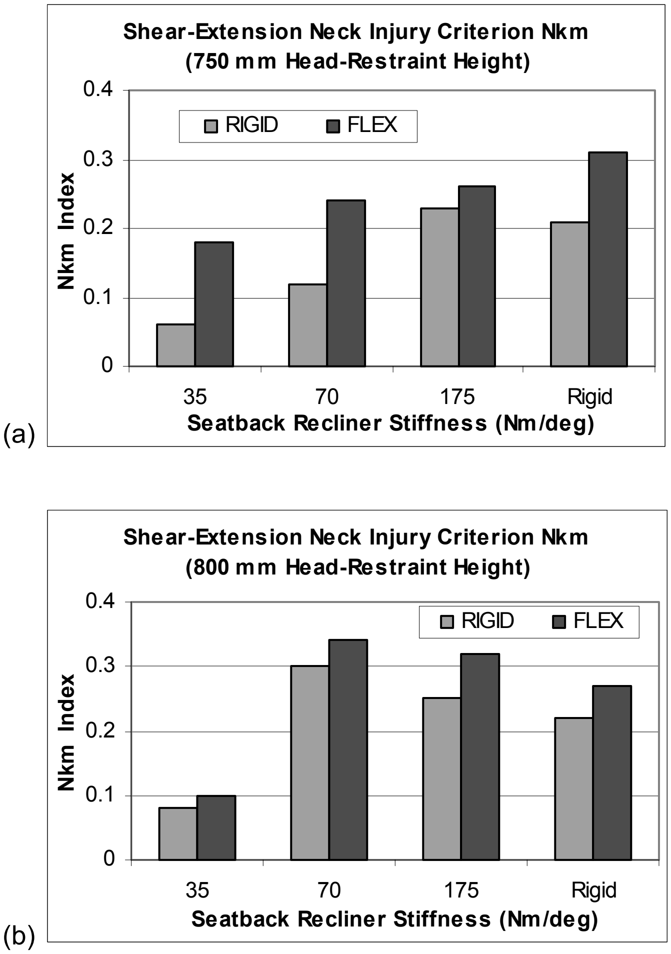

Figure 12. Maximum shear-extension neck injury criterion Nkm for RIGID and FLEX head restraints at 750 mm (a) and 800 mm (b) positions

DISCUSSION

The present study investigated the effects of head restraint structural rigidity on the whiplash injury risk in rear impact collisions. The results demonstrated that a head restraint with a more rigid internal structure and attachment generally leads to a lower neck injury risk compared to a more flexible one as measured by the maximum upper neck posterior shear force, upper and lower neck extension bending moment, tension-extension neck injury criterion (upper neck), shear-extension neck injury criterion (upper neck), and relative head-torso extension angular displacement.

The experimental sled simulation of the rear impact tests in the present investigation included a wide range of seat recliner stiffness. This was designed to capture the characteristics of a wide variety of seat recliner mechanisms available in passenger cars, including the fixed rear passenger seats which do not allow seatback rotation. The results from the present study show that a more rigid head restraint has a consistent neck protective advantage across all the recliner stiffness ranges.

The present study included head restraint heights of 800 mm and 750 mm as specified in existing motor vehicle safety standards. The more rigid head restraint appears to have a consistent neck protective advantage as measured by the parameters examined except for the shear force in the lower position (Figure 6a). The difference in the upper neck shear force at that height was small and inconsistent.

A selected number of biomechanical measures and injury criteria for the neck were considered in the present study. The neck injury criterion Nij was used because it was the first comprehensive criterion using dummy load cell data (Kleinberger et al. 1998; Eppinger et al. 2000). The injury threshold values used in Nij were based on more severe cervical spine injuries than those that commonly occur in low-speed rear impacts. Hence, its use in this study was only for qualitative comparison rather than quantitative assessment. The shear-extension neck injury criterion Nkm was specifically developed to assess the neck injury risk in rear impact situation (Schmitt et al. 2001) although its injury threshold values still require further validation. Some studies have found that the lower neck extension bending moment was most sensitive to seat design, crash severity, and neck injury outcome (Prasad et al. 1997; Heitplatz et al. 2003). The head extension angular displacement relative to the upper torso was also evaluated 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.

There are other proposed neck injury criteria for rear impact that were not considered in the present study. One of those criteria, NIC, is based on the assumption that fluid flow within the spinal canal causes pressure gradients that are injurious to the nerve roots. It accounts for the translational acceleration and velocity of the occipital condyles relative to the T1 vertebra, respectively (Bostrom et al. 1996). The Neck Displacement Criterion (NDC) is another, which is based on the relative translational and rotational displacements between the occipital condyles and the T1 vertebrae (Viano et al. 2002). Both of these aforementioned criteria use mechanical parameters that are difficult to measure without video analysis, which is impractical for certain types of testing.

The present investigation has used a Hybrid III dummy in sled testing. Although Hybrid III family of dummies are initially developed for frontal impact testing, they are the most widely used dummies in the world and the only family of dummies adapted in the motor vehicle safety standards by the US government. More recently developed dummies such as RID2 and BioRID are designed specifically for rear impact testing. Those rear impact dummies are more compliant in extension rotation and rearward translation of the head relative to the torso. Hence, RID2 and BioRID dummies would be expected to exhibit more relative motion than the Hybrid III dummy under the same test conditions. Therefore, head restraint rigidity would have a greater effect on those two more compliant dummies than the Hybrid III in reducing relative motion.

This study only has examined one of many factors related to the performance of head restraint. There are many other properties of the head restraint such as shape, size, and position relative to the head that can affect its performance. The effects of those factors may not be apparent by simple geometric or static measurement. Complete evaluation of head restraint system performance would require dynamic testing.

The results from the present study should be considered preliminary. Only two head restraint systems were tested. The performance of the head restraint is a complex problem influenced by many biomechanical factors including the seatback, recliner mechanism, dummy, test condition, and injury criteria. The conclusions from this study are therefore only applicable to the test conditions and assessment tools used. Further investigation into this issue is necessary to reach more comprehensive and definitive conclusions.

CONCLUSION

Using an instrumented dummy and deceleration sled, this study has demonstrated that a more rigid head restraint in its structural design and attachment may have an advantage for neck protection in relatively low-speed rear impact vehicular collisions. This conclusion holds true for a wide range of seatback recliner stiffness levels and different head restraint heights.

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