# DAIMLERCHRYSLER

DaimlerChrysler Corporation
Matthew C. Reynolds
Director
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July 25, 2000

Mr. Stephen R. Kratzke
Associate Administrator for Safety Performance Standards
National Highway Traffic Safety Administration
400 Seventh Street S.W. Room #5401D
Washington. DC 20590

Dear Mr. Kratzke:

Re: NHTSA Docket No. 00-7013 - Notice 1
FMVSS 208, Occupant Crash Protection

During our meeting with you and members of your staff on June 22, 2000, we discussed our findings regarding the non-biofidelic response of the Hybrid III dummy neck when loaded by an air bag. Our presentation summarized the work discussed in the attached paper, "Nature of Hybrid III Dummy Neck Response Due to Air Bag Loading." This paper provides additional information regarding the airbag-test dummy interaction issues documented by DaimlerChrysler. These issues were the basis of DaimlerChrysler's comments to the FMVSS 208 SNPRM (Docket #6407-44, submitted December 23, 1999) and our subsequent petition for reconsideration of the FMVSS 208 final rule (Docket #7013-22, submitted June 26, 2000).

If there are questions regarding this submission, or if agency staff wish to discuss these research findings further, please contact Mr. W. R. Edwards of my staff at (248) 576-7303.

Sincerely,

W R Edwards

for Matthew C. Reynolds

cc: Stan Backaitis
Docket Management (electronic submission)

Attachment

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# Nature of Hybrid III Dummy Neck Response Due to Air Bag Loading

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**Abstract**

The Hybrid III family of dummies is used to estimate the response of an occupant during a crash. One recent area of interest is the response of the neck during air bag loading. However, the biomechanical response of the Hybrid III dummy neck was based on inertial loading during crash events when the dummy is restrained by a seat belt and/or seat back. Contact loading resulting from an air bag was not considered when the Hybrid III dummy was designed. This paper considers the effect of air bag loading on the 5th percentile female Hybrid III dummies. The response of the neck is presented in comparison to currently accepted biomechanical corridors.

The Hybrid III dummy neck was designed with a primary emphasis on appropriate flexion and extension responses using the corridors proposed by Mertz and Patrick. They formulated the mechanical neck performance requirements as the relationship between the moment at the occipital condyles and the rotation of the head relative to the torso when the neck is subject only to belt loading or seatback loading. Air bag loading is significantly different than belt loading or seatback loading, because there is more than one load path on the head. During air bag loading (with or without belt restraint), the dummy neck shows significantly different responses than those seen in the Mertz and Patrick tests. The neck experiences second mode bending during air bag loading as opposed to the first mode bending seen in seat belt and/or seat back loading.

The Hybrid III 5th female dummy is frequently used to estimate the response of small stature occupants to air bags. This paper examines the Hybrid III 5th female dummy neck responses due to air bag loading. The neck responses were found to be highly dependent on how the air bag interacts with the dummy. Three patterns of interaction were observed and studied: air bag directly loading the head, air bag trapped under the chin during the deployment process and air bag trapped behind the jaw of the dummy head. This paper also presents the results of some modifications to the head/neck design of the Hybrid III 5th female dummy to prevent air bag entrapment.

## 1. INTRODUCTION

The members of the Hybrid III dummy family are used as human surrogates in automotive frontal impact tests to assess the performance of different occupant restraint systems. Although frontal air bags have been mandated as supplemental restraints in automobiles, the evaluation of the human-air bag interaction is not straightforward. Most current efforts to study air bag-occupant interaction use the Hybrid III family of dummies and the associated injury risk assessment criteria. One of the areas of concern in these studies is the head/neck response of the

Hybrid III due to interaction with a deploying air bag. The neck of the Hybrid III dummy needs to have sufficiently human-like response characteristics to be useful in evaluating the human response to deploying air bags. Problems associated with the Hybrid III dummy head/neck design and the neck response during air bag loading make it difficult to accurately assess the response to human subjects. The main issue is the significant departure, in terms of anthropometric characteristics of the head/neck region, between the Hybrid III and the human occupant [1]. The exposed horizontal surface in the chin-jaw region and the near vertical cavity between the jaw and the neck, provide unrealistic reaction surfaces for loading due to an inflating air bag, resulting in unrealistic neck deformation.

The Hybrid III dummy neck was designed with emphasis on appropriate flexion and extension response with respect to the corridors proposed by Mertz and Patrick [2]. They formulated the mechanical performance requirements of the neck as the relationship between the moment at the occipital condyles and the rotation of the head relative to the torso. These corridors are the only existing estimates for the response of the cervical spine in bending. Neck response in these corridors is primarily due to inertial loading of the head. During impact, the seatbelts or the seatback, restrain the motion of the torso, while the neck deforms like a cantilever beam, in first mode bending, due to the motion of the head. However, as the results in this paper indicate, air bag loading can result in a significantly different neck deformation than that seen in the Mertz and Patrick tests [2]. The neck can experience second mode bending during air bag loading, especially when the air bag is trapped in the chin-jaw region or in the jaw-neck cavity. Since the neck response of human subjects due to interaction with deploying air bags is not known, the possibility of occurrence of second mode bending of the Hybrid III dummy neck can not be supported a priori as biofidelic.

An investigation of the response of small stature occupants to air bags, by using the Hybrid III $5^{th}$ percentile female dummy, was conducted to better understand the modes of interaction between the air bag and the dummy neck. The neck response was found to be highly dependent on the nature of the air bag's interaction with the dummy's head/neck region. There are essentially three modes of interaction between the air bag and the dummy's head/neck region for the same test set-up (described below). The response varies significantly from test to test. Consequently, the dummy response could be considered chaotic with three distinct modes, but no way to predict which mode would occur in a given test. In the first mode, the air bag directly loads the head. In the second mode, the air bag is trapped in the chin-jaw region during the deployment process. In the third mode, the air bag is trapped behind the dummy's jaw in the jaw-neck cavity. In all three cases, moment distributions resulting in the second bending mode are generated, which may not represent the response of a human subject. Design modifications to the neck region of the Hybrid III $5^{th}$ percentile female dummy to prevent one or both of the last two modes of air bag/occupant interactions were investigated.

## 2. TEST METHODS

A series of static air bag deployment tests were conducted to investigate the loading of the head/neck region of the Hybrid III $5^{th}$ percentile female dummy during air bag deployment. The choice of the static environment was based on its simplicity and ease of obtaining the desired initial alignment of the dummy relative to the air bag module. A typical test setup is shown in Figure 1. The dummy was placed, leaning towards the instrument panel, in a full-forward passenger seat.

Only a frontal passenger air bag was used to restrain the dummy (i.e., without seatbelts). Two different air bag systems were used, a “standard” system and a “depowered” system (20% reduction in the slope of the "standard" system tank pressure time history). To increase the likelihood of the air bag catching in the chin-jaw region and/or behind the jaw, in the jaw-neck cavity, the seat was raised two inches from its standard position and the head was rotated approximately 20 degrees forward. While it is recognized that this test setup is artificially contrived and is unlikely to occur in a vehicle crash, it is a useful test condition to illustrate the different modes of air bag/dummy interactions that could occur in a dynamic crash test.

A standard Hybrid III $5^{th}$ percentile female dummy, a TMJ head skin, and a SAE neck shield were used for the baseline tests. The TMJ skin was intended to prevent the air bag entrapment in the chin-jaw region as well as in the jaw-neck cavity. The head skin, in both the chin-jaw area and in the cavity behind the jaw, was painted with different colors of chalk. The colors transferred to the air bag were checked to determine whether the air bag was entrapped under the chin or behind the jaw. The dummy was instrumented with upper and lower neck load cells (Models 1716 and 2150, respectively, Denton, Inc.). Head, chest and pelvic accelerations were measured using linear accelerometers (Model 7264-2000, Endevco, Inc.). The transducer data were processed according to SAE J211. The three-dimensional motion of the head and the chest were computed using the method developed by Nusholtz, et al.[3]. High-speed video cameras and film cameras, capable of 1000 frames per second, were used to monitor the head/neck and air bag interactions from the lateral direction and the oblique posterior direction above the head.

The head external loads resulting from air bag impact were calculated using the head accelerations and the upper neck loads. Figure 2 shows a free-body diagram of the dummy head with internal reactions ($F_N$ and M), external force ($F_E$), and acceleration (a). The neck reaction force and moment is measured with the upper neck load cell and the acceleration is measured with the accelerometer located at the center of gravity of the head. The eccentricity between the center of gravity and the load cell gage plane, allows the equilibrium equations to be solved for the unknown external force.

In addition to the study of the airbag-head/neck interaction, the neck response due to impulse loading by means of a seatbelt, looped around the jaw line of the Hybrid III $5^{th}$ percentile female dummy (Figure 18), was also studied. By choosing appropriate locations of the seatbelt on the jaw line, it was presumed possible to simulate the effect of the airbag trapping, either in the chin-jaw region or in the jaw-neck region. It was expected that the local pressure of the seatbelt on the head skin of the dummy around the jaw line would not allow the seatbelt to slip out as easily as an airbag would. Consequently, much higher forces and moments, than those possible with a hypothetical equivalent airbag loading, could be felt by the dummy's neck before the seatbelt would slip out from under the jaw line. In other words, the seatbelt test for neck response is unlikely to simulate the airbag loading adequately. However, the test can be useful to some extent in simulating the effect of change in stiffness of nodding blocks on continued engagement or disengagement of the seat belt under the jaw line. The impulse loading with the seatbelt was carried out with three different sets of nodding blocks in the dummy's head-neck zone, a standard set, a set with very low stiffness compared to the standard set and another set very stiff compared to the standard set.

## 3. RESULTS

A summary of the test results is shown in Table 1. The peaks in the time-histories of the upper neck loads, the head resultant acceleration, the HIC values over a 15 ms time interval, the chest resultant acceleration and the chest deflections are included. Due to a large number of tests conducted, only the average values and the standard deviations are presented for the three typical modes of head/neck and air bag interactions. The air bag contacted the head at approximately the same time in all three cases (15 ms after air bag firing). The head and chest started to accelerate, and the forces in the neck started to increase immediately after the contact. The interactions between the air bag and the occupant, and the head/neck kinematics are shown in Figure 3-5. Time history data are plotted for three representative tests in Figure 6-12. The head/neck response in each mode of interaction is described in the following sections.

Interaction Mode 1

In the first mode, the air bag directly loads the head (Figure 3), leading to a flexion moment at the neck. The neck shear is positive (Figure 6), which implies that the head moves rearwards relative to the chest. The head external shear is in the anterior-posterior direction (Figure 7) and causes the head to move rearwards. The neck axial force is insignificant in magnitude and changes from compression to tension (Figure 8). The head external axial force is in the superior-inferior direction (Figure 9) and causes the head to move downwards. The applied external loads are both larger than the corresponding neck forces. This indicates that neck loads are from the air bag loading alone for this air bag and head/neck interaction pattern. The upper neck moment is in pure flexion (Figure 10). The dependence of the upper neck moment on the head rotation relative to the chest is compared to the flexion corridor proposed by Mertz, et al., [4] for Hybrid III 5$^{th}$ percentile female dummy (Figure 11). In this mode of interaction, the moment-rotation relationship falls outside the corridor almost immediately after the head rotation starts. The torso is accelerated rearward by the deploying air bag (Figure 12). The free body diagrams of the head and neck during air bag loading are shown in Figure 14(A). The combined upper and lower neck bending moments cause the neck to flex into a reflected S-shape in second mode bending.

Interaction Mode 2

In the second mode, the air bag contacts the head under the chin (Figure 4). (Note: Due to the poor resolution of pictures in this test series, a photograph of a test conducted with a neck skin is shown in Figure 4.) The bag is trapped under the chin during the deployment. The neck shear changes to negative (Figure 6), which implies that the head moves forward relative to the torso. However, the head external shear is still in the anterior-posterior direction (Figure 7). This implies that a major portion of neck shear comes from the inertial loading of the head on the neck. Tension load is present in the neck (Figure 8). The head external axial force is in the inferior-superior direction (Figure 9) and causes the head to move upward. The external axial load is close in magnitude to the neck tension. This indicates that the contribution to the neck tension is primarily due to the air bag loads on the head/neck area and not due to the inertial loading of the head. The upper neck moment is in pure extension (Figure 10). The upper neck moment as a function of head rotation relative to the chest is compared to the extension corridor proposed by Mertz, et al., [4] (Figure 11). The test data again falls outside the corridor, even at very small head rotation values. The chest acceleration is mainly in the rearward direction (Figure 12). The free body diagrams of the head and neck during air bag loading are shown in Figure 14(B). The forces and moments again cause a second mode bending in the neck. However, in this mode, the deformed shape of the neck is S-shaped as opposed to the reflected S in Mode 1.

Interaction Mode 3

For the third case, the air bag contacts the head below the chin (Figure 5). The fabric is entrapped in the hollow area between the neck and the jaw. As the bag continues to inflate, pressure is built up within the entrapped portion of the air bag. The air bag drags the head forward and upward. The neck shear is negative to a higher degree than in Mode 2 (Figure 6), which implies that the head moves forward relative to the torso. The head external shear changes to the posterior-anterior direction (Figure 7) and causes the head to move forward. The neck shear is larger than the external shear load. This indicates that a portion of the neck shear comes from the inertial loading of the head on the neck. However, the major contribution to the neck shear is due to the air bag loads on the head/neck area as a result of the trapped air bag. Tension is evident in the neck (Figure 8). The head external axial force is in the inferior-superior direction (Figure 9) and causes the head to move upward. The external axial load is close in magnitude to the neck tension. This indicates that the contribution to the neck tension is due to the air bag loads on the head/neck area. The upper neck moment is in extension (Figure 10). The response of upper neck moment as a function of head rotation relative to the chest is compared to the extension corridor (Figure 11). The observed response falls outside the corridor starting with very small values of rotation. The chest acceleration changes from the backward direction to the forward direction (Figure 12). This change is due to the air bag being trapped behind the jaw and forcing the chest forward while the head rotates. If the air bag is trapped behind the jaw, the head external shear load is in the posterior-anterior direction and causes high neck shear. The friction between the air bag fabric and the material of the dummy skin, and the force from the trapped air bag behind the jaw contribute to the head external shear force.

The magnitude of the nominal friction coefficient during air bag contact was estimated (Figure 13). This was done by dividing the external shear load by the external axial load. The peak ratio is approximately 1.8. This value is significantly higher than that would be observed in a bench test. This indicates that significant external shear load is due to the trapped air bag behind the jaw. The entrapped air bag causes high neck shear that is only seen in this mode of air bag and head/neck interaction. The free body diagrams of the head and neck during air bag loading are shown in Figure 14(C). The neck deformed into S-shape, similar to Mode 2, but with a larger curvature.

Modifications to the Hybrid III 5$^{th}$ Percentile Female Dummy Neck

The SAE recommended TMJ head skin and neck shield did not prevent the air bag from becoming trapped in the chin-jaw region or in the jaw-neck cavity. To eliminate this artifact of air bag/head/neck interactions (air bag snagging under the chin and behind the jaw), the 5$^{th}$ percentile female dummy neck was modified using two different approaches. The first approach used a modified head/neck skin. Using neck parts from the Hybrid II 50$^{th}$ percentile male dummy, additional skin and rubber and a head skin from the Hybrid III 5$^{th}$ percentile female dummy, a neck surface was formed that extended from the jaw to the upper torso (Figure 15). This modification prevented the air bag from becoming caught in the chin-jaw region or in the jaw-neck cavity. This modification produced insignificant change in the results of the pendulum extension test. The neck moment versus head rotation response was inside the specified biomechanical extension corridor. However, it is believed that the flexion response will be compromised due to interference to the motion of the head by the upper torso jacket. Eleven static air bag tests were conducted using this modified neck. All resulted in neck responses similar to Mode 1 (Table 2). The second approach added a pair of aluminum extensions to the jaw (Figure 16). This design also eliminated the air bag from becoming caught behind the jaw, but not from under the chin. This modification did not affect either the flexion or the extension response in the standard pendulum calibration tests. Eight static air bag tests were conducted using this modified head design (Table 2). Five tests (62.5%) resulted in neck loads similar to Mode 1 and three tests (37.5%) resulted in neck loads similar to Mode 2. The Mode 3 tupe of air bag-neck interaction did not occur in tests using the aluminum jaw extensions.

Two different air bag systems were used in this study. One was a standard system and the other was a depowered system as described above. The three typical air bag and head/neck interaction patterns all were observed with both air bags. The average values and standard deviations of occupant response were obtained for these two different air bag systems for the three typical head/neck and air bag interactions (Table 3). These two different air bags produced similar neck loads in Mode 1. However, the depowered air bag created higher neck extension moments in Mode 2 and Mode 3.

## 4. DISCUSSION

In a human subject, the neck loads are generated by active cervical muscles which resist head movement. Typically, in a relaxed occupant, there is a time lag between the onset of external loading and the initial muscle activity. Snyder, et al., [5] measured the reflex times of various cervical muscles to a sudden, unanticipated stimulus. The reflex time was defined as the time lag between the onset of head acceleration and a distinct increase in muscle activity. The average reflex times for neck flexor and extensor muscles were 77 and 66 ms, respectively, for male subjects and 66 and 63 ms, respectively, for female subjects. Szabo and Welcher [6] found that initial muscle activity occurred approximately 100 to 125 ms after the moment of bumper contact during low speed rear impacts. Ono, et al. [7] found that the average start time of neck flexor muscle discharge was 79 ms.

When a human subject with relaxed muscles is exposed to an unexpected air bag deployment, the head is likely to start rotating with little resistance from the upper neck. Consequently, significant head rotation will occur with little bending moment. After a certain time period, the cervical muscles will start to activate and build up reactive forces, leading to neck loads. However, this will occur late in the air bag deployment event. On the contrary, the upper neck moments obtained from air bag tests, using the Hybrid III 5$^{th}$ percentile female dummy, showed pronounced moment values with little head angular motion (Figure 11). It appears that the moment versus angular motion relationship in these air bag loading cases is not representative of the likely biomechanical response of a relaxed human subject. The neck response of the Hybrid III dummy appears to be an artifact due to the current neck design rather than a phenomenon contributing potentially to neck injury.

The flexion and extension response corridors developed by Mertz and Patrick [4] are the biofidelity basis for Hybrid III dummy neck. The human volunteers, whose response was used to devise these extension corridors all appear to have experienced some degree of neck tensing in anticipation of the impact. Consequently, the extension response corridors may not be representative of the response of relaxed occupants subjected to unexpected air bag loading. The plateau portion represents the maximum moment that the neck muscles can generate in resisting head motion before appreciable head rotation occurs. The initial bending stiffness for the 5$^{th}$ percentile female is 2.06 N-m/degree for flexion and 0.77 N-m/degree for extension. After reaching a certain point, the neck muscle yields and the head keeps rotating without an increase in the bending moment. When the normal articular voluntary range of motion of the neck is reached, the neck ligaments and/or passive stretch of the neck muscles, increases the bending resistance of the neck. The lower portion of the corridors reflects the elastic behavior of the ligaments and muscles as well as energy dissipation of the muscles during rebound. These corridors represent the neck response in the particular cases of restraint with either the seatbelt or the seatback. However, they were not developed for evaluating air bag loading and therefore may not be suitable for this application.

The upper neck moments obtained from these series of air bag tests were plotted as a function of head rotation relative to the chest and compared to the corridors developed by Mertz and Patrick. Figure 12 shows significant differences for both the flexion mode and the extension modes. The upper neck loads build up very quickly once the air bag contacts the head. For Mode 1, the initial stiffness of neck flexion was 7.2 Nm/degree, as compared to 2.06 Nm/degree for the flexion corridor. For Mode 2 and Mode 3, the initial extension stiffness was 3.5 Nm/degree and 6.5 Nm/degree, respectively. The observed extension stiffness from last two cases was much higher than the value from the extension corridor (0.77 Nm/degree). The dummy neck showed much stiffer responses in both flexion and extension during air bag loading than would be exhibited in seatbelt loading or seatback loading.

The differences in head/neck response in the air bag tests and the biomechanics corridors could be due to the difference in the bending modes that occur in the two tests modes. Recall that the response corridors were solely generated due to the restraint by the belt or the back of the seat depending upon whether it is a forward or a rear impact respectively. Head motion loads the neck like a cantilever beam with a mass at the free end. No external forces on the head, such as those due to a deploying air bag, are present. In this case, the neck response is primarily due to head inertial loading, and the neck experiences first mode bending. During air bag loading, significant loads are applied directly to the head, which causes the neck to experience second mode bending. The neck deforms in either a reflected S-shape or an S-shape due to combined upper and lower neck bending moments (Figure 14). Thus, the corridors based on first mode bending of the neck are not adequate for air bag applications. Biomechanical data are needed to address the unique characteristics of neck muscle loading, head angular position and multiple load paths to the head and neck in the air bag testing environment.

Another factor, which could contribute to the observed head/neck response seen in the air bag tests, is the excessive stiffness in the dummy's neck. The human occipital condyle joint appears to have considerable laxity, which allows it to experience significant rotation before it can sustain a substantial moment across the joint. However, the current Hybrid III neck exhibits considerable bending resistance at its occipital condyle joint [8, 9]. This lack of compliance may allow large moments to be transmitted to the neck by the head without significant relative motion. In a human subject, articulation of the neck is accomplished through muscle pairs, which are attached to the skull, the individual vertebra, and the torso. These muscle pairs respond in various group actions to produce the desired movement of the head and neck. The muscle tones are simulated in the dummy through a pair of rubber nodding blocks and four rubber neck discs. Nightingale, et al., [9] studied the effects of upper neck joint stiffness on measured moments in the Hybrid III dummy during air bag loading using MADYMO occupant simulations. The standard dummy model was modified to simulate the axial and rotational stiffness of the ligamentous human cervical spine (no muscles). They found that decreasing the rotational stiffness had a dramatic effect on the extension moment.

By comparison, the NHTSA advanced dummy, THOR, allows significant head rotation without substantial moment in the occipital condyle joint [10]. Comparing the neck response of THOR dummy and Hybrid III dummy in vehicle crashes, the magnitude of the bending moment at the occipital condyle joint in THOR dummy was approximately 1/6 of the Hybrid III for both driver and passenger (Figure 17). This is one possible solution to the neck artifacts seen in the Hybrid III. However, the THOR is a new dummy that has not been evaluated thoroughly.

To resolve the problem of lack of compliance at the occipital condyle joint in the Hybrid III dummy, the rubber nodding blocks of the Hybrid III $5^{th}$ female dummy were softened. A series of drop tower tests were conducted. The upper neck moment as a function of head rotation relative to the chest was obtained. For the same amount of head rotation, the softer nodding block showed a 10-20% reduction in upper neck extension moment. However, there is not enough space between the nodding blocks and the head to allow substantial rotation before developing higher moments. Other modifications are needed to allow the head to rotate without significant moment in the head/neck joint during the initial air bag loading.

Standard system and depowered air bag systems were used in this test series. The three typical air bag and head/neck interaction patterns all were observed with both air bags. Both air bags produced similar neck loads in Mode 1, but the depowered air bag created higher neck extension moments in Modes 2 and 3. While this indicates that the neck response is not necessarily a function of air bag power for depowering in this range, differences in response are expected for more extensively depowered systems. Due to the limited sample size, no conclusion can be drawn regarding the effects of the air bag power on the head/neck response.

## 5. CONCLUSIONS

This paper considered a limited study that analyzed the response of the Hybrid III neck to air bag loading. The study focused on one area of air bag loading under very specific and artificial conditions. More investigation is needed before results can be generalized. However, the results indicate that changes may be needed in the design of the Hybrid III family of dummies to accurately represent the response of human subjects.

The test series presented in this paper indicates that the dummy head/neck response depends strongly on the manner in which the air bag interacts with the dummy's head. If the air bag is not trapped in the chin-jaw region or behind the jaw, in the jaw-neck cavity, the head is pushed rearward and downward, resulting in neck flexion and compression. If the air bag is caught in the chin-jaw region, the head is pulled forward and upward, subjecting the neck to extension and tension to some degree. If the air bag is entrapped behind the jaw in the jaw-neck cavity, the head is again dragged forward and upward, subjecting the neck to extension and tension to a very high degree. The SAE recommended TMJ head skin and the neck shield do not prevent air bags from being trapped behind the jaw or under the chin. However, two different head/neck structure modifications developed in this study demonstrate practical ways to prevent the air bag from being trapped in the chin-jaw region or in the jaw-neck cavity.

Even if unnatural interactions due to the air bag being trapped behind the jaw or under the chin are prevented, the dummy head/neck response due to interaction with a deploying air bag is still significantly different than that would be expected in a relaxed human occupant. Air bag tests result in pronounced neck bending moments in the dummy with little head rotation relative to torso, a phenomenon which is unlikely to occur in relaxed human subjects.

In the tests presented in this paper, the dummy neck was subject to second mode bending during air bag deployment. Currently available biomechanical flexion and extension response corridors of Hybrid III dummy neck do not appear applicable to the neck response in air bag tests. Biomechanical data are needed to address the neck responses during air bag loading to accurately assess the injury potential to human subjects.

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**Figure 1**. Typical Test Setup

**Table 1.** The Average Values of the Peak Response

| | Statistic | Upper Neck Response | | | Head | HIC15 | Chest | Chest |
|---|---|---|---|---|---|---|---|---|
| | | Fx | Fz | My | Res. Acc. | | Res. Acc. | Deflection |
| | | (N) | (N) | (Nm) | (g) | | (g) | (mm) |
| Air Bag Loads the Head Directly (Case 1, 21 tests) | **Avg.** | **939** | **1050** | **68** | **80** | **131** | **36** | **20** |
| | S.D. | 243 | 632 | 17 | 22 | 67 | 8 | 4 |
| Air Bag Caught Under the Chin (Case 2, 6 tests) | **Avg.** | **-2217** | **3551** | **-121** | **91** | **266** | **36** | **23** |
| | S.D. | 509 | 808 | 39 | 11 | 122 | 8 | 4 |
| Air Bag Entrapped Behind the Jaw (Case 3, 9 tests) | **Avg.** | **-5133** | **4446** | **-206** | **95** | **373** | **40** | **30** |
| | S.D. | 373 | 619 | 21 | 14 | 261 | 5 | 2 |

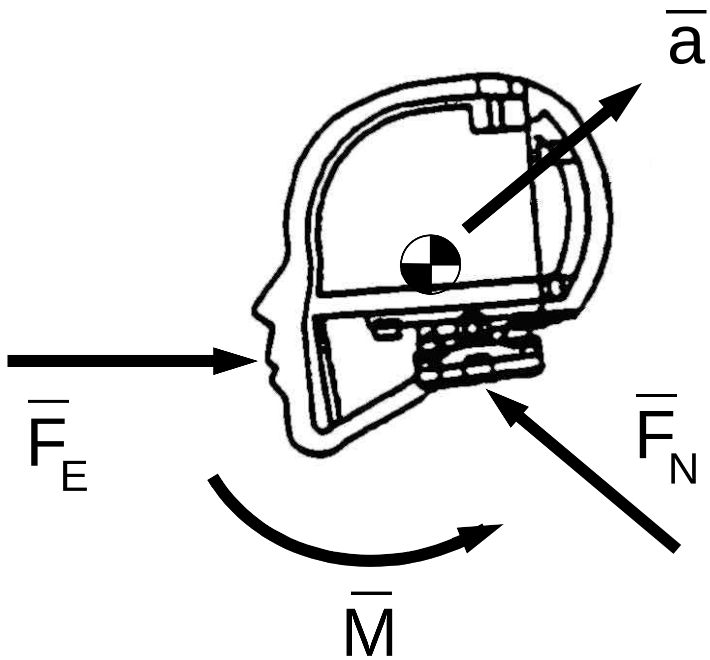


**Figure 2**. Free Body Diagram of Dummy Head.

**Figure 3**. Air bag Loading the Head Directly.

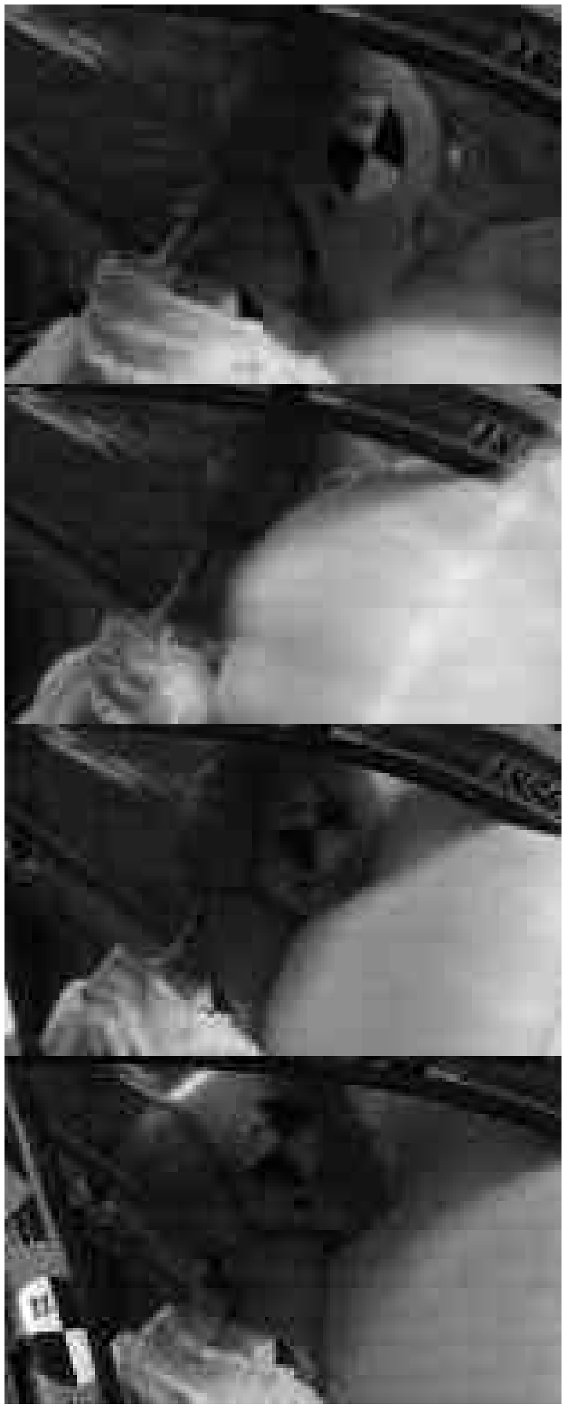

**Figure 4**. Air bag Caught Under the Chin.

**Figure 5**. Air bag Entrapped Behind the Jaw.

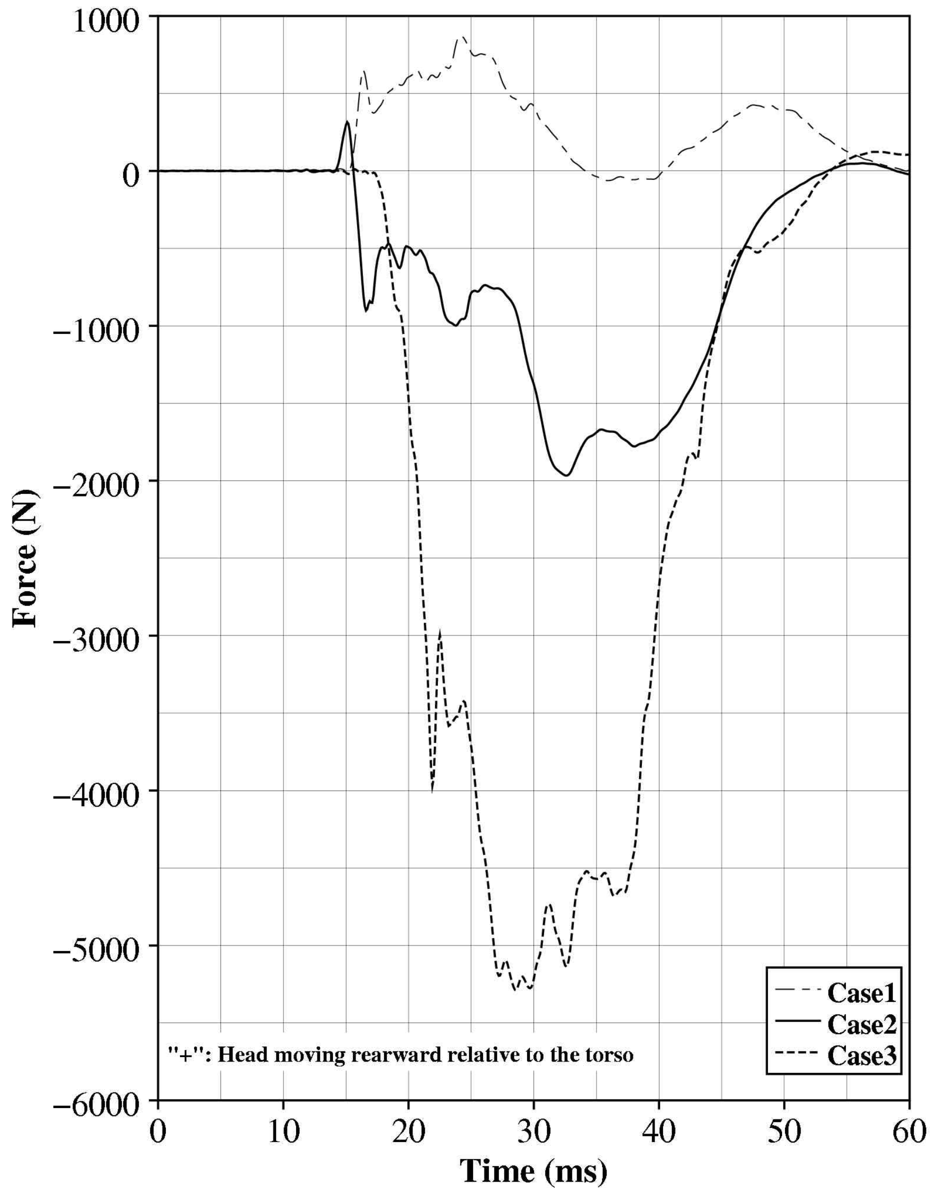


**Figure 6**. Upper Neck Shear Force.

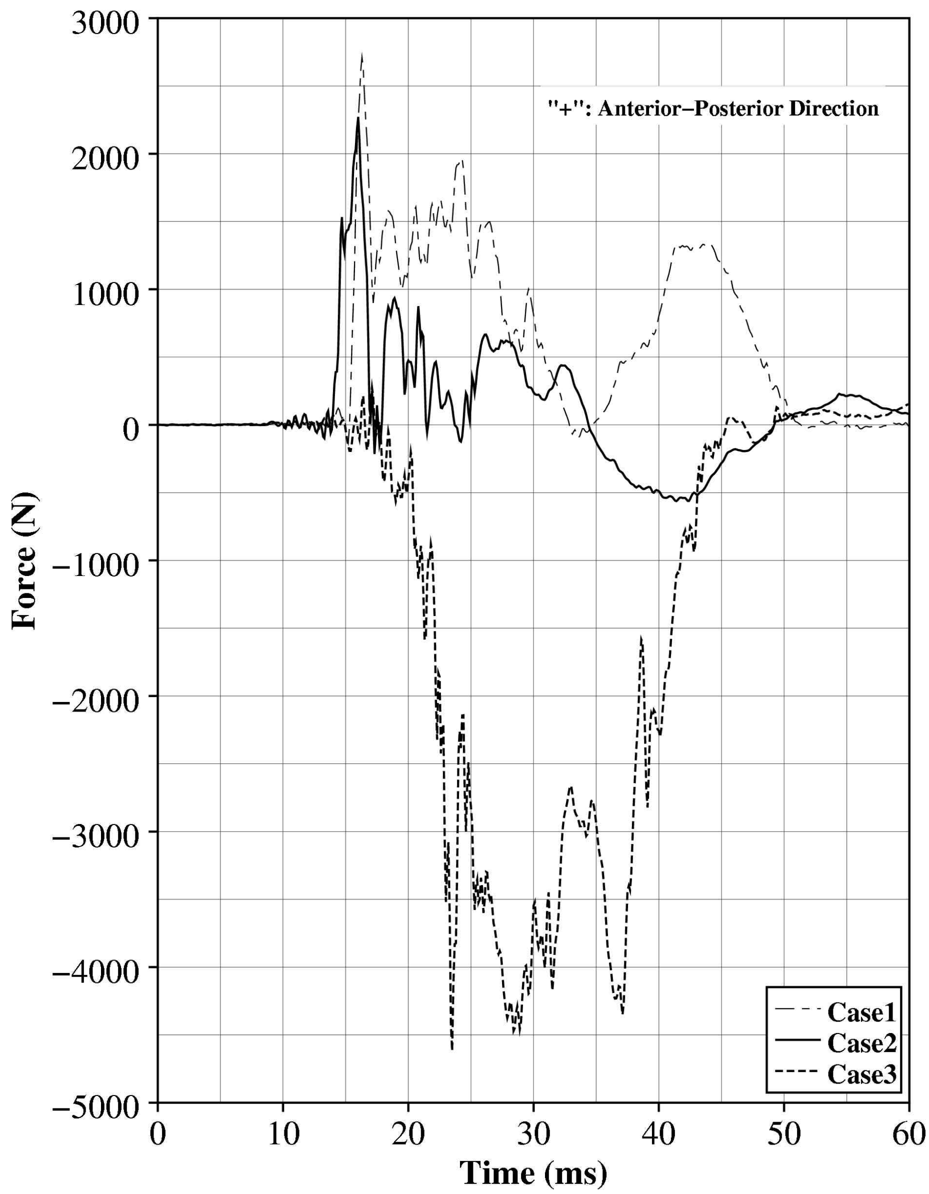


**Figure 7**. Head External Shear Force.

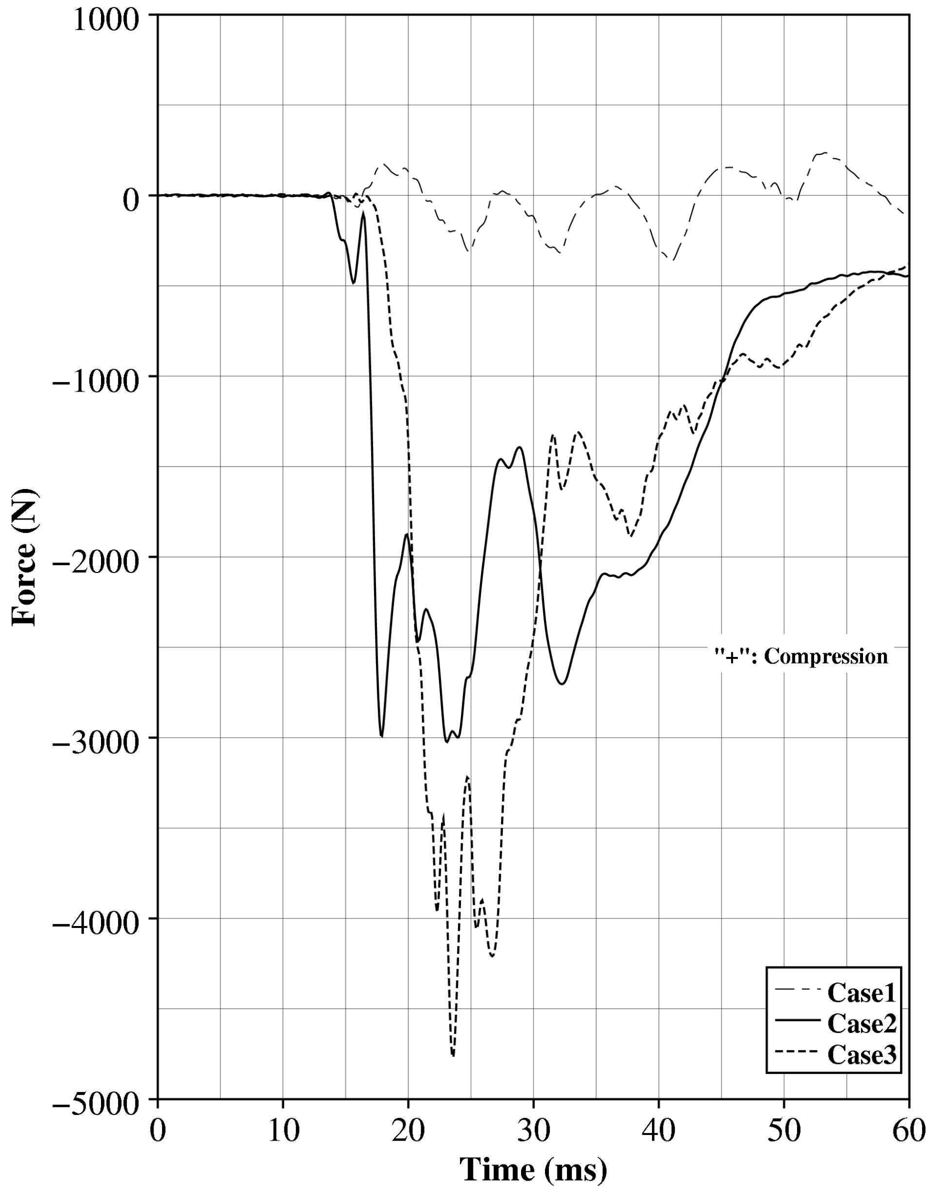


**Figure 8**. Upper Neck Axial Force.

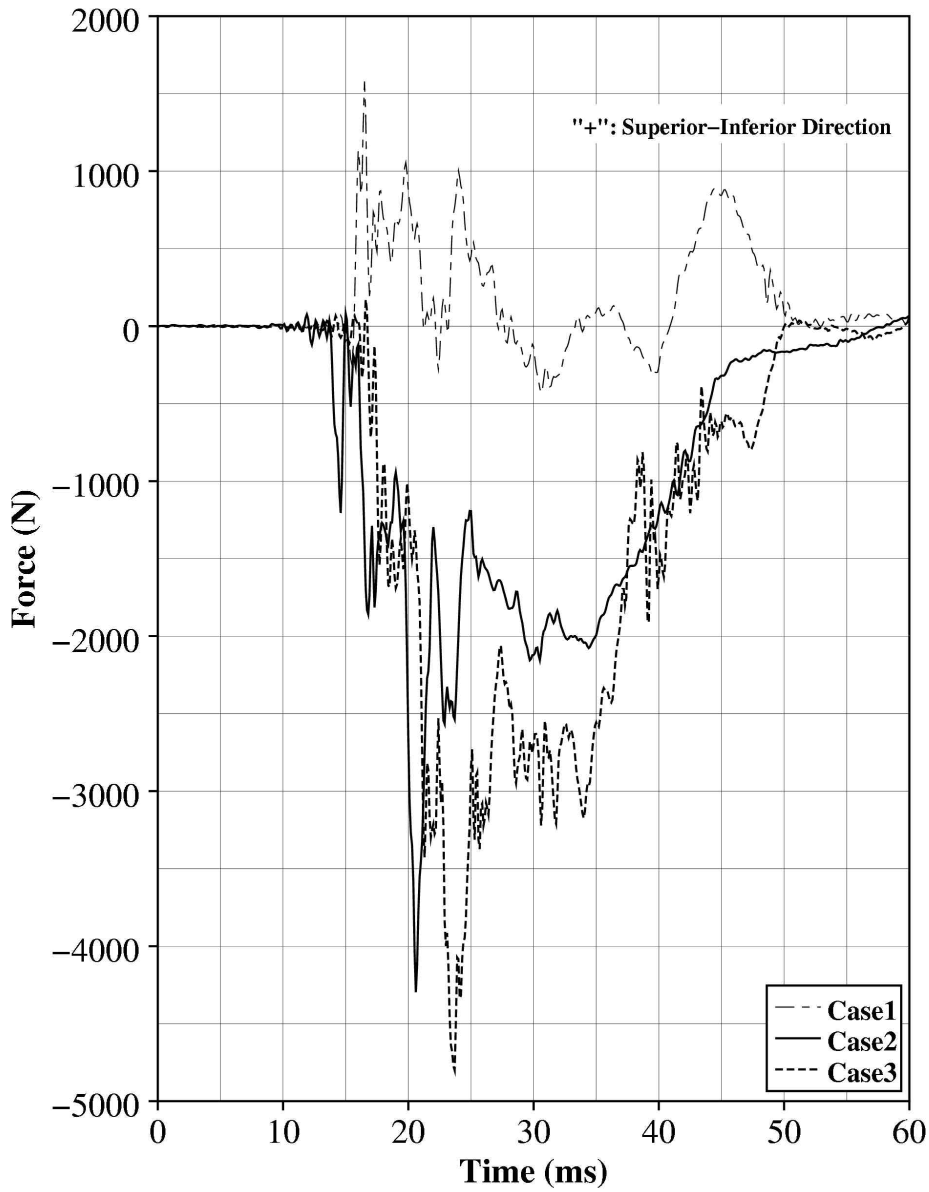


**Figure 9**. Head External Axial Force.

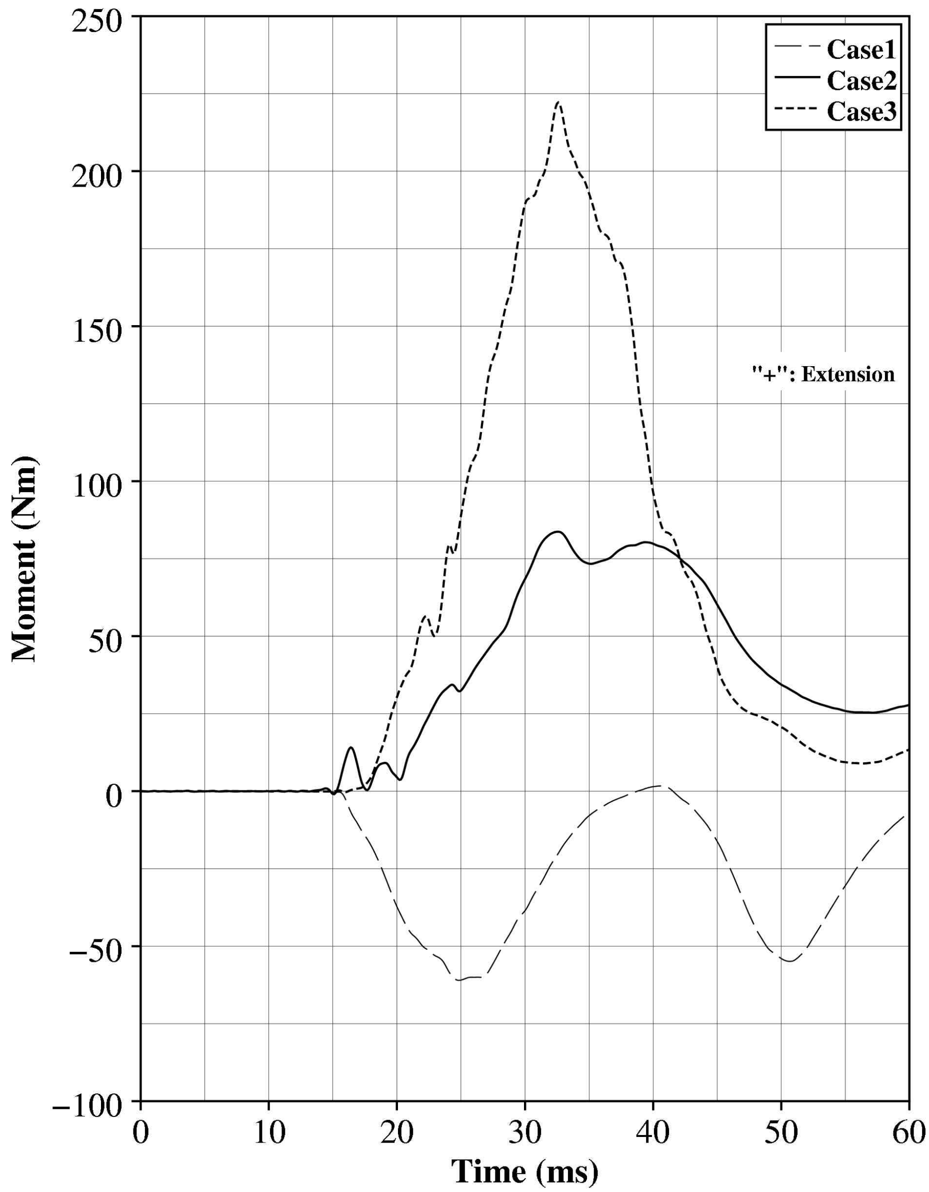


**Figure 10**. Upper Neck Bending Moment.

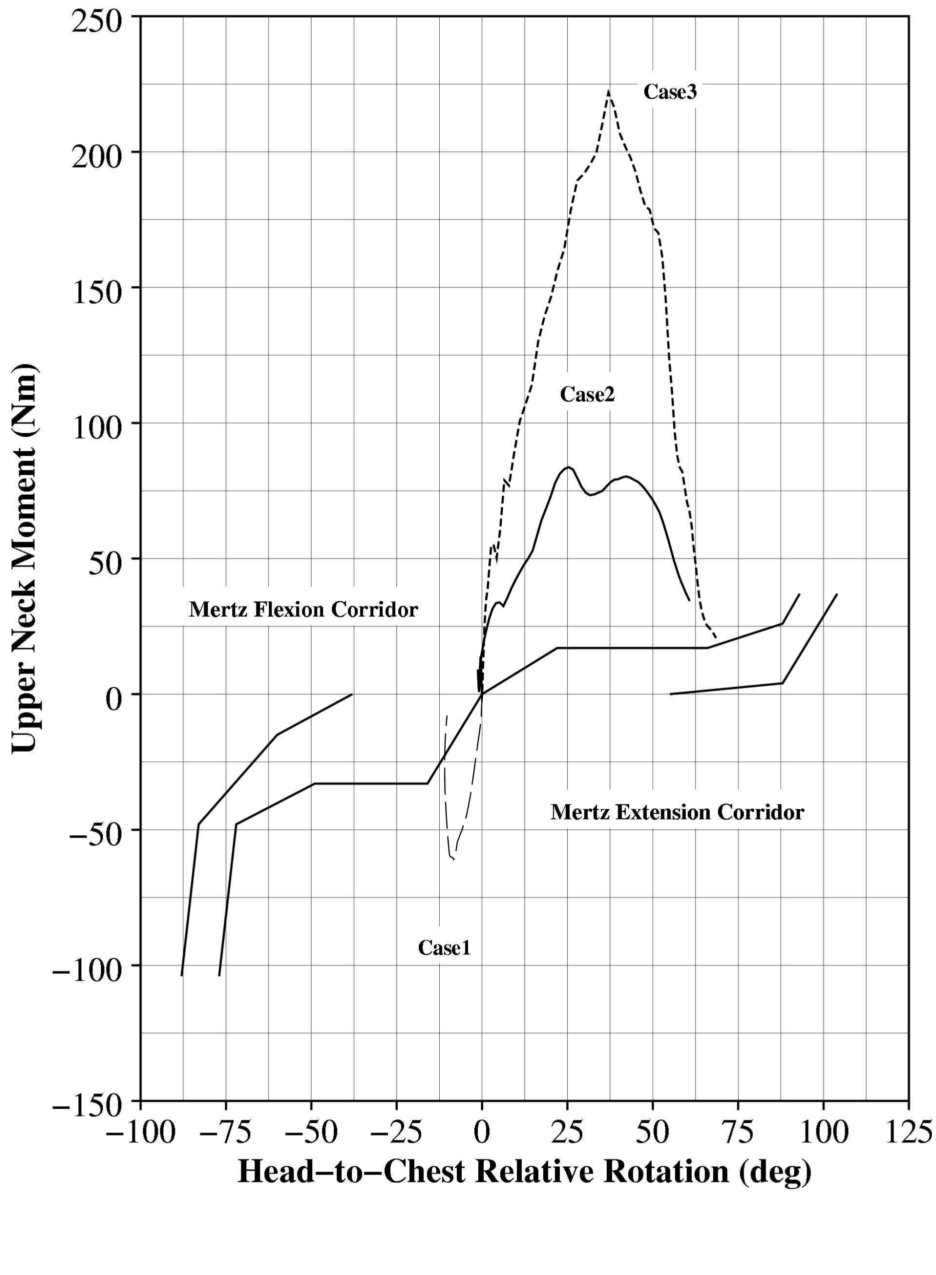


**Figure 11**. Upper Neck Moment vs. Head-to-Chest Relative Rotation.

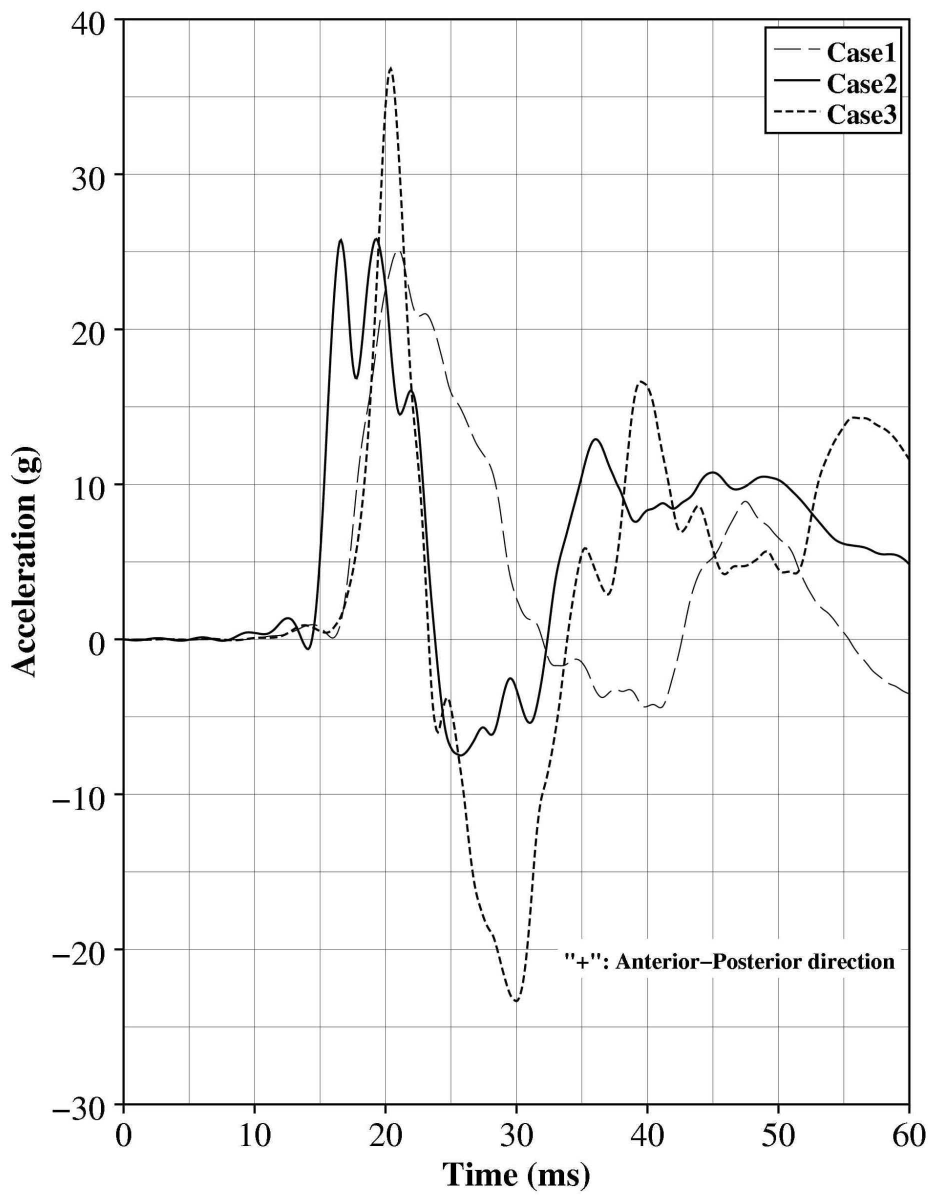


**Figure 12**. Chest X Acceleration.

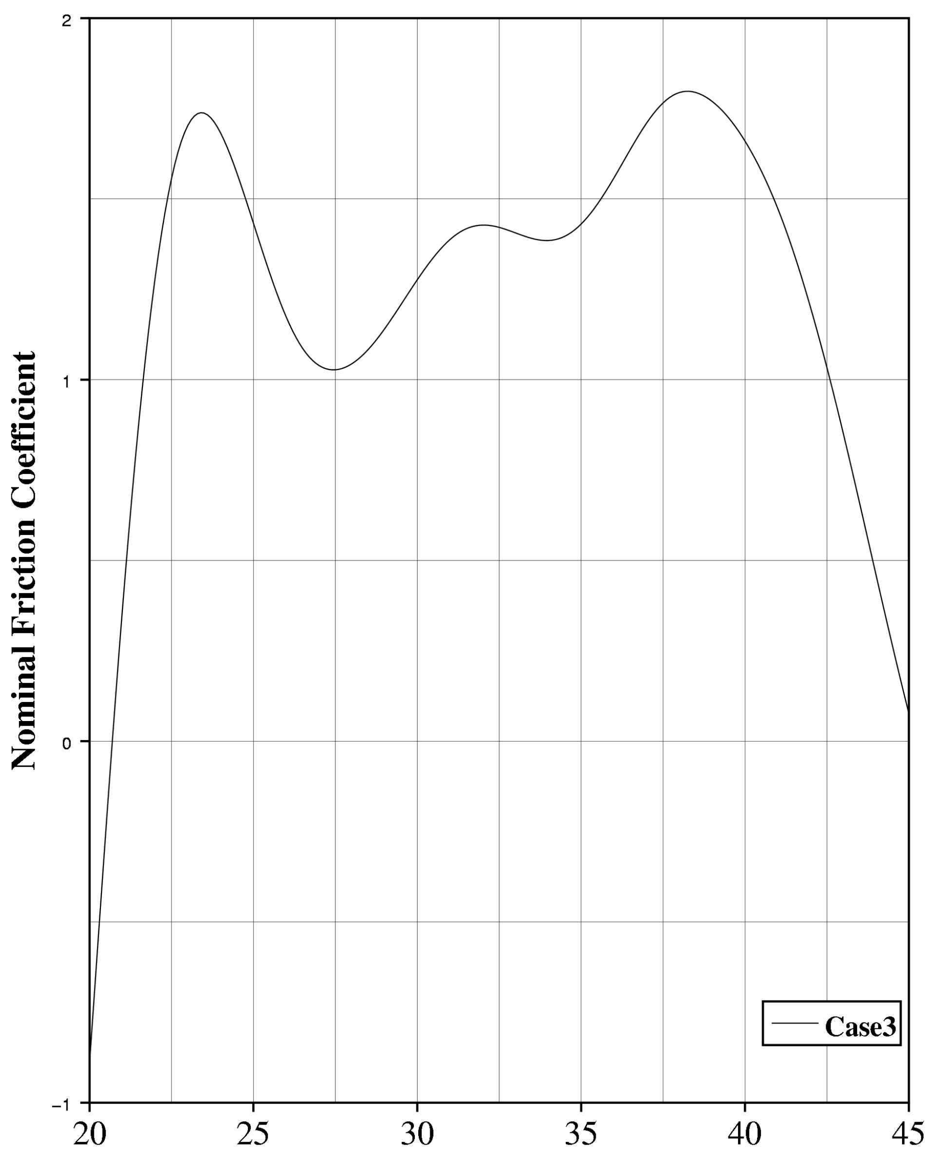


**Figure 13**. Estimate of the Friction Coefficient.

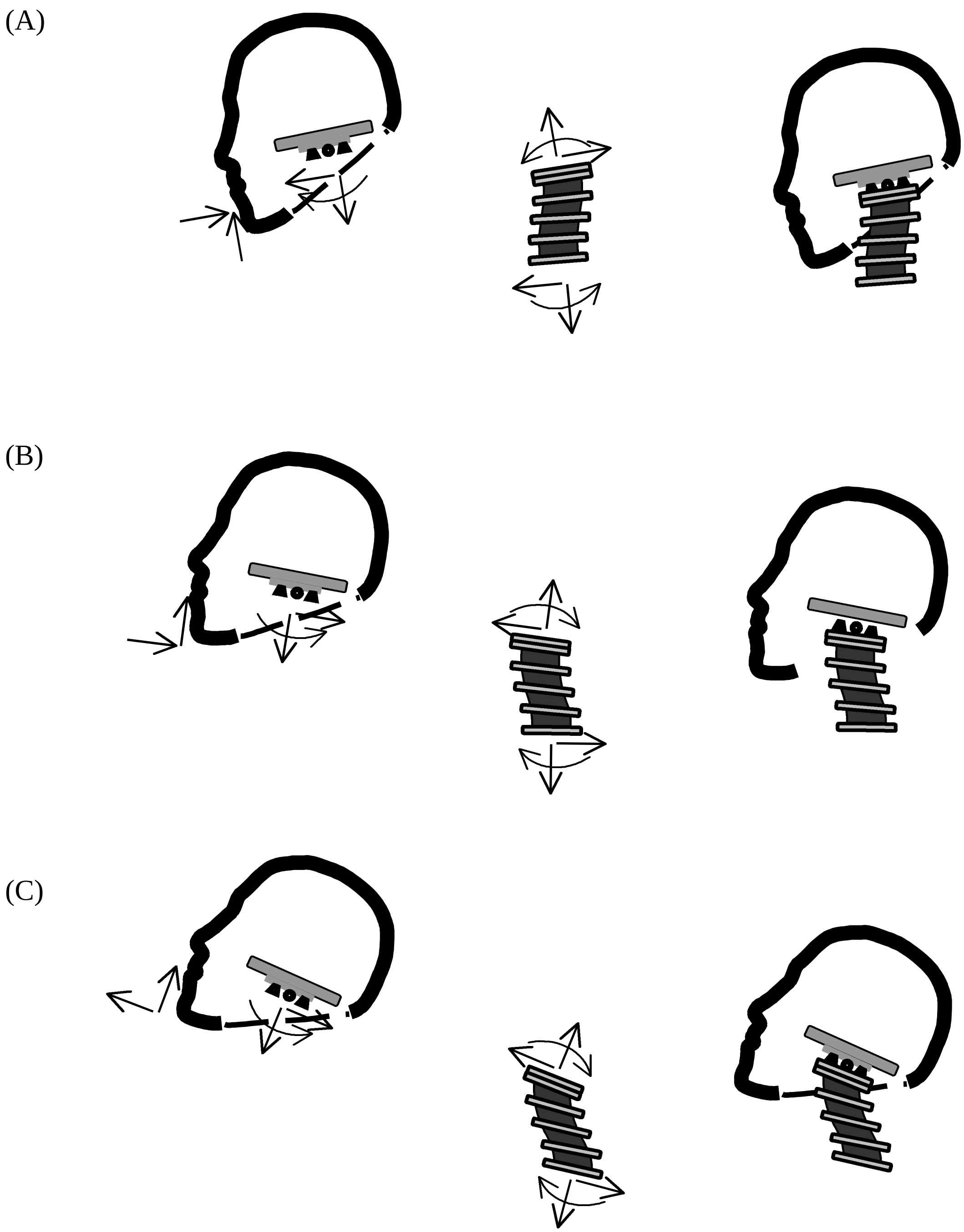


**Figure 14**. Free Body Diagrams of the Head and Neck, Showing the Deformed Shape of the Neck.

(A) Case 1: Airbag Loading the Head Directly.
(B) Case 2: Airbag Caught under the Chin.
(C) Case 3: Airbag Caught behind the Jaw.

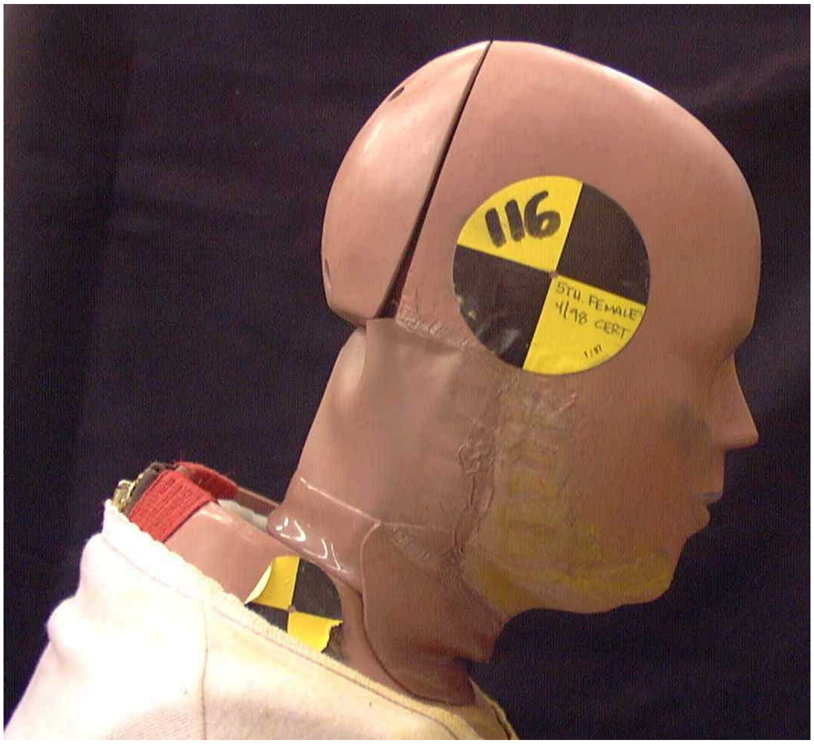


**Figure 15**. Modified Head/Neck Skin.

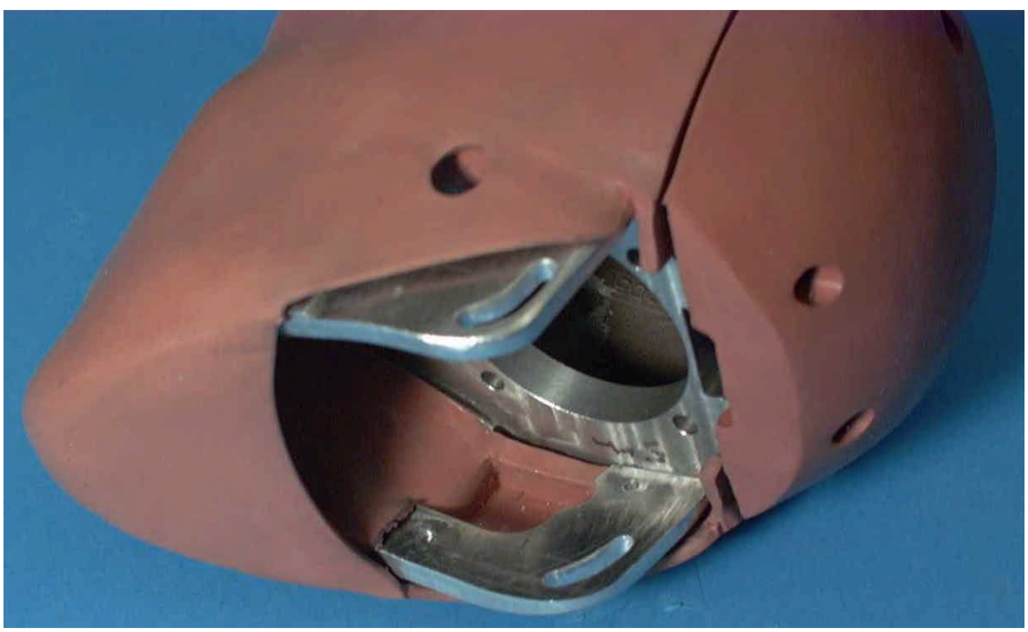

**Figure 16**. A Pair of Aluminum Patches Added to the Head.

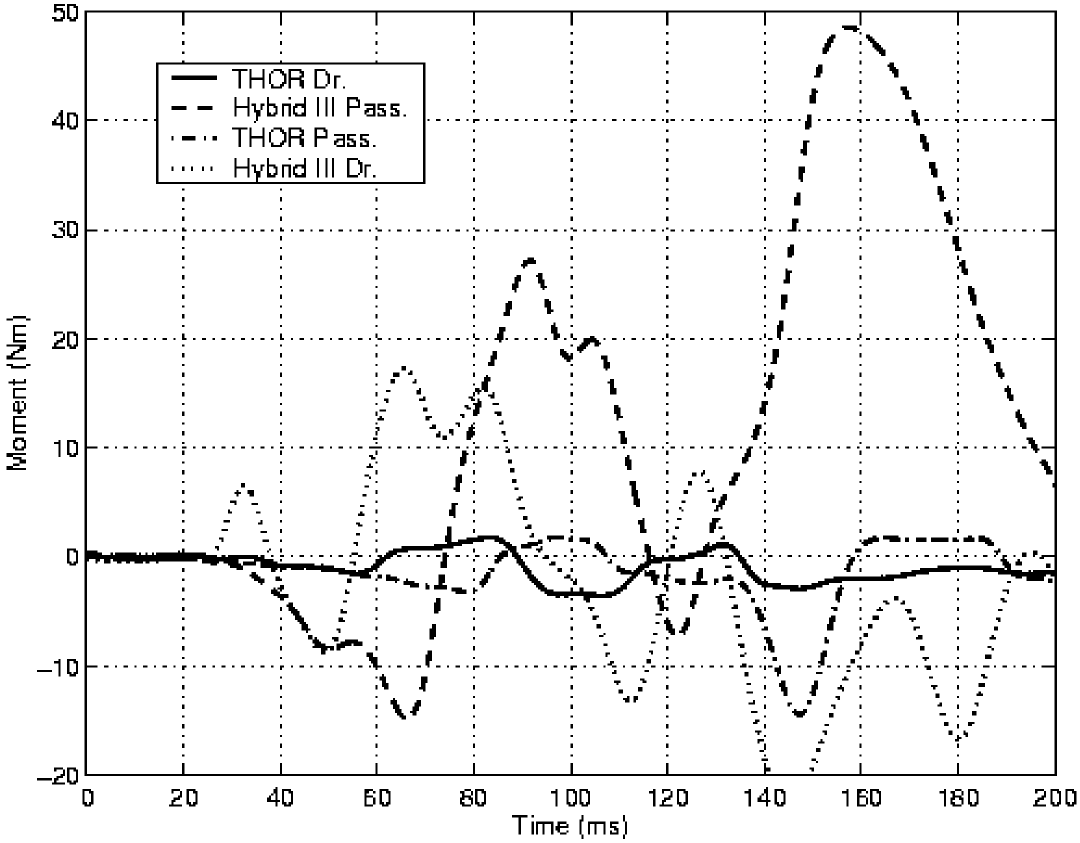


**Figure 17**. Neck Moment Comparison of THOR Dummy and Hybrid III Dummy [10].

**Table 2.** Peak Response in Airbag Tests with Neck Structure Modifications

| Test # | Airbag System | Head Skin | Neck Skin | Upper Neck Responses Fx (N) | Fz (N) | My (Nm) | Head Resultant (g) | HIC15 | Chest Resultant (g) | Chest Deflection (mm) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | standard | standard | Mod. 1 | 836 | 2384 | 48 | 93 | 136 | 42.7 | 28 |
| 2 | standard | standard | Mod. 1 | 1231 | 1291 | 73 | 92 | 164 | 47.8 | 22 |
| 3 | standard | standard | Mod. 1 | 1070 | 1590 | 72 | 110 | 232 | 46.4 | 13 |
| 4 | standard | standard | Mod. 1 | 859 | 1319 | 60 | 115 | 263 | 46.2 | 21 |
| 5 | standard | standard | Mod. 1 | 960 | 650 | 71 | 93 | 195 | 44.7 | 20 |
| 6 | standard | standard | Mod. 1 | 1159 | 1235 | 76 | 101 | 176 | 47 | 27 |
| 7 | standard | standard | Mod. 1 | 1006 | 724 | 77 | 90 | 176 | 40 | 24 |
| 8 | standard | standard | Mod. 1 | 1134 | 1496 | 89 | 112 | 187 | 43 | 22 |
| 9 | standard | standard | Mod. 1 | 843 | 1565 | 64 | 72 | 147 | 34 | 23 |
| 10 | standard | standard | Mod. 1 | 860 | 677 | 67 | 94 | 148 | 34 | 20 |
| 11 | standard | standard | Mod. 1 | 1206 | 717 | 83 | 106 | 165 | 34 | 22 |
| **Avg.** | | | **Mod. 1** | **1015** | **1241** | **71** | **98** | **181** | **42** | **22** |
| **S.D.** | | | | **153** | **531** | **11** | **12** | **38** | **5** | **4** |
| 1 | depowered | TMJ | Mod. 2 | 837 | 522 | 81 | 53 | 65 | 27 | 17 |
| 2 | depowered | TMJ | Mod. 2 | 725 | 441 | 58 | 63 | 54 | 31 | 15 |
| 3 | depowered | TMJ | Mod. 2 | 723 | 533 | 59 | 60 | 49 | 28 | 15 |
| 4 | depowered | TMJ | Mod. 2 | 647 | 408 | 57 | 54 | 38 | 24 | 14 |
| 5 | depowered | TMJ | Mod. 2 | 543 | 561 | 40 | 47 | 58 | 31 | 19 |
| **Avg.** | | | **Mod. 2** | **695** | **493** | **59** | **55** | **53** | **28** | **16** |
| **S.D.** | | | | **109** | **65** | **15** | **6** | **10** | **3** | **2** |
| 6 | depowered | TMJ | Mod. 2 | -2721 | 3910 | -132 | 103 | 201 | 43 | 22 |
| 7 | depowered | TMJ | Mod. 2 | -2460 | 3493 | -178 | 93 | 200 | 29 | 22 |
| 8 | depowered | TMJ | Mod. 2 | -2678 | 4165 | -151 | 104 | 203 | 31 | 21 |
| **Avg.** | | | **Mod. 2** | **-2620** | **3856** | **-154** | **100** | **201** | **34** | **22** |
| **S.D.** | | | | **140** | **339** | **23** | **6** | **2** | **8** | **1** |


**Figure 18.** Impulse Loading with a Seatbelt Looped at the Jaw Line

**Table 3.** The Average Values of the Peak Responses of Two Airbag Systems

| | Airbag System | Statistics | Upper Neck Responses Fx (N) | Upper Neck Responses Fz (N) | Upper Neck Responses My (Nm) | Head Res. Acc. (g) | HIC15 | Chest Res. Acc. (g) | Chest Deflection (mm) |
|---|---|---|---|---|---|---|---|---|---|
| Bag Loads the Head Directly | Standard Airbag (12 tests) | Avg. | 1034 | 1177 | 73 | 95 | 179 | 41 | 22 |
| | | S.D. | 161 | 553 | 13 | 15 | 37 | 6 | 4 |
| | Depowered Airbag (9 tests) | Avg. | 811 | 881 | 62 | 60 | 68 | 29 | 17 |
| | | S.D. | 282 | 722 | 20 | 9 | 38 | 5 | 3 |
| Bag Caught Under the Chin | Standard Airbag (2 tests) | Avg. | -2031 | 3739 | -92 | 80 | 379 | 40 | 27 |
| | | S.D. | 89 | 1010 | 11 | 6 | 189 | 13 | 6 |
| | Depowered Airbag (4 tests) | Avg. | -2311 | 3457 | -136 | 96 | 210 | 35 | 21 |
| | | S.D. | 628 | 845 | 41 | 9 | 17 | 6 | 1 |
| Bag Entrapped Behind the Jaw | Standard Airbag (2 tests) | Avg. | -4638 | 5240 | -192 | 115 | 789 | 45 | 31 |
| | | S.D. | 52 | 551 | 11 | 3 | 307 | 3 | 1 |
| | Depowered Airbag (7 tests) | Avg. | -5275 | 4220 | -210 | 90 | 254 | 39 | 29 |
| | | S.D. | 283 | 437 | 22 | 11 | 32 | 5 | 2 |