HYBRID III DUMMY NECK RESPONSE TO AIR BAG LOADING

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ABSTRACT

This paper discusses issues related to the Hybrid III dummy head/neck response due to deploying air bags. The primary issue is the occurrence of large moment at the occypital condyles of the dummy, when the head-rotation with respect to the torso is relatively small. The improbability of such an occurrence in humans is discussed in detail based on the available biomechanical data. A secondary issue is the different anthropometric characteristics of the head/neck region of the Hybrid III dummy when compared to humans.

Different modes of interaction between the deploying air bag and the Hybrid III dummy's neck are discussed. Key features of the dummy's response in these interaction modes have been described in light of the laxity of the atlanto-occypital joint and the effect of the neck muscle pairs. Issues for improving the biofidelity of the Hybrid III dummy's neck response due to deploying air bags are discussed.

INTRODUCTION

At present, the occupant response in automotive accidents is estimated by studying the response of the Hybrid III family of dummies in simulated crashes. With the increasing provision of air bags in today's, and possibly future fleet of vehicles, the biofidelity of the Hybrid III dummy neck response to air bag loading has taken on special significance. The characteristics of human response to interaction with deploying air bags however, is not well understood, and consequently, the design of Hybrid III family of dummies may require updating.

The current head-neck design of the Hybrid III dummies may not provide a reliable prediction of the response of human subjects due to a deploying air bag. The major issue, is the occurrence of large moments in the neck of the dummy, with very little rotation of the head relative to the torso. Such a response is unlikely in humans due to different load resisting mechanisms in humans when compared to those in the dummy. Another issue is the significant departure in the anthropometric characteristics of the head/neck region, between the Hybrid III dummy and the humans. The exposed horizontal surface in the chin-jaw region and the near vertical cavity between the jaw and the neck, as well as, the vertical surface behind the chin, provide unrealistic reaction surfaces for loading by an inflating air bag, potentially resulting in unrealistic neck-deformation. Although, the secondary issue of the air bag penetrating the chin-neck-jaw cavity has received some attention in terms of proposals for neck shield design, the fundamental issue of discrepancy in the moment-rotation relationship between that of the Hybrid III dummy and humans has received limited attention.

Melvin et al [1] in their study of air bag interaction with out-of-position drivers used a vinyl-nitrite neck-skin and a Neoprene chin filler on the Hybrid III 5th percentile female dummy, in an attempt to prevent the air bag from entering the neck-chin-jaw cavity. The spine of the dummy was modified in order to allow it to slouch without off from the seat. The authors did not present a detailed analysis to show if their neck shield design successfully prevented the air bag from entering the neck-chin-jaw cavity or not. They did however mention that in their efforts, stiffer neck shields generated alternate load paths to the head, shunting the upper neck load cells, thereby affecting the readouts. The authors did not address the issue of high moments in the neck at low angles of head rotation.

Morris et al [2] have studied three neck shield concepts for Hybrid III 5th percentile female dummy in driver seat, in order to assess their ability to prevent the air bag from entering into the neck-chin-jaw cavity. The concepts were: the standard head skin with a molded foam neck shield, the TMJ head skin (SAE terminology, referred as modified neck-skin in the paper [2]) with a foam neck wrap, and the TMJ head skin with an integrated neck shield. The integrated neck skin was formed by welding vinyl skin to the TMJ head skin such that it wraps around the neck and goes under the jacket. The authors report that the standard head skin with the molded foam neck shield passed the extension calibration test but failed the flexion calibration test. The TMJ head skin with the foam neck wrap passed both the extension and the flexion calibration tests. The TMJ head skin with the integrated neck shield could not be tested for calibration because the gripping under the jacket could not be simulated. Amongst the three neck shield designs considered, the TMJ head skin with the integrated neck shield was the best in preventing the air bag from entering the neck-chin-jaw cavity. However, this design was considered to have inhibited the upper neck load cells from measuring the true loads by restricting the head motion. The authors did not address the improbability of occurrence of high moments at the occipital condyles in humans for very little head rotation, a characteristic exhibited by the Hybrid III dummy.

Kang et al [3] have recently presented their study of the moment-rotation relationship of the Hybrid III dummy head/neck, due to a deploying air bag, by comparing it with the corridors proposed by Mertz and Patrick [4]. The moments at the occipital condyles of the Hybrid III dummy, in certain modes of air bag-neck interaction, go out of the Mertz and Patrick [4] corridors, with very little head rotation relative to the torso. Kang et al [3] also studied two neck shields for their potential to prevent air bags from entering the neck-chin-jaw cavity. One of their neck shield designs consisted in welding a Hybrid II 50th percentile male dummy head skin's chin and neck portion to the underside of the Hybrid III 5th percentile female dummy's standard head skin. The entrance of the air bag into the neck-chin-jaw cavity was successfully prevented. Due to the stiffness of the Hybrid II dummy's chin and neck portion of the head skin, certain neck air bag interaction modes were completely eliminated. It was however not clear if, and to what extent, the neck load cell measurements were affected. Further, the neck shield passed the extension calibration test, while it failed the flexion calibration test due to interference with the jacket. The second neck shield design studied by Kang et al [3] targeted the elimination of a specific air bag neck interaction mode, namely the entrapment of the air bag behind the jaw, in the near vertical jaw-neck cavity. Aluminum patches were used as extensions to the jaw of the dummy's head, preventing the air bag from getting trapped behind the jaw, although not preventing it from getting into the chin-jaw cavity and exhibiting another, less severe, air bag neck interaction mode. This neck shield design successfully passed both the flexion and the extension calibration tests.

From the literature it appears that the attempts to prevent the air bag from entering the chin-neck-jaw cavity of the Hybrid III dummy, have been the major focus. This is not surprising because such efforts do not need fundamental changes to the dummy's head/neck design and only involve the design of neck shields. However, it must be noted that neck shields, which prevent the air bag from entering the chin-neck-jaw cavity effectively, also pass the neck calibration tests, and which do not interfere with the neck load measurements have yet to be designed. Attempts to improve the moment-rotation relationship of the Hybrid III dummy's neck are conspicuous by their absence in reported literature, although this might be a more fundamental way of dealing with the problem of large moment at the occypital condyles at small head rotation angles.

The Hybrid III dummy neck was designed by limiting its flexion and extension responses, described as the relationship between the moment at the occipital condyles and the rotation of the head relative to the torso, to the corridors proposed by Mertz and Patrick [4]. The neck-deformation mode considered by Mertz and Patrick [4] was generated by the motion of the head relative to torso, when the torso was restrained either by the seat belt or the seat back. This essentially results in first bending mode in the dummy's neck. Air bag loading is significantly different from the seatbelt or the seatback loading, because of much larger extent of interaction of the air bag with the head, neck and torso. Further the anthropometric characteristics of the current Hybrid III dummy's neck-jaw complex, is different from that of humans. The neck-chin-jaw cavity in the Hybrid III dummy is easily accessible to the deploying air bag. The large reaction surface offered by the dummy's neck-chin-jaw cavity to the air bag, results in different neck deformation mode when compared to that due to the seatbelt or the seatback loading.

The current Hybrid III dummy's neck response is represented solely through beam-bending, although the laxity of the atlanto-occypital joint and the action of the muscle pairs imply that two separate load paths should be included in the response of the head/neck system. In case of air bag loading, the combination of the beam-like neck structure tuned to first bending mode (based on Mertz and Patrick [3] corridors), and the possibility of entrapment of the air bag within the neck-chin-jaw cavity, can result in second bending mode bending of the dummy's neck. This in turn can lead to high neck moments at very low angles of head rotation relative to torso.

In what follows, is a description of different air bag-neck interaction modes likely with the Hybrid III. More details can be found in Ref.3.

Figure 1. Typical Test Setup

Although the results presented pertain to the Hybrid III 5th percentile female dummy, the arguments are general and apply to the 50th percentile as well as the 95th percentile male. The discussion of the Hybrid III dummy neck bending response in light of the laxity of the atlanto-occypital joint [7,8] and the role of the muscle pairs [9], is then presented. A comparison of the neck response of the Hybrid III dummy, with that of the THOR dummy [10], is also included.

AIR BAG NECK INTERACTION MODES

The results presented here are a summary of a series of static, air bag deployment tests conducted to investigate the head/neck response of the Hybrid III 5th percentile female dummy due to a deploying air bag [3]. The study was limited to frontal passenger air bags, and the seat belts were not used. The test setup is shown in Figure 1. The dummy was placed, leaning towards the instrument panel, in a full-forward passenger seat. The seat was raised two inches from its normal position. The dummy's position was chosen to enhance the probability of air bag entrapment in the neck-chin-jaw cavity.

A standard Hybrid III 5th percentile female dummy, with a TMJ head skin, and a SAE neck shield [2] were used for the baseline tests. The head skin referred to as "modified" in Ref.2 is referred to as TMJ head skin in this paper. The neck shield was a thin, "mouse pad like" material, which was wrapped around the neck. The head skin, in both the chin-jaw area and in the cavity behind the jaw, was painted with chalks of different colors in order to determine whether the air bag was entrapped under the chin or behind the jaw. High-speed video cameras and film cameras were used to monitor the head/neck and air bag interactions.

The head external loads resulting from air bag impact were calculated using the head accelerations and the upper neck loads. Based on the analysis of the measured response time-histories, the high-speed films, and the colored chalk marks on the air bag, the modes of interaction between the dummy’s neck and the deploying air bag were deciphered. Three modes of air bag-dummy interaction: were identified: interaction mode 1, the neck loads are generated primarily from the air bag loading the front of the head, interaction mode 2, the neck loads are generated primarily from the air bag trapped under the chin, and interaction mode 3, the neck loads are generated primarily from the air bag trapped behind the jaw. The three modes of air bag-neck interaction are shown schematically in Figures 2-4. The figures show the configurations at the instant of peak loads (max N_{ij}) in each mode of interaction. Typical time history data are plotted for three typical representative tests in Figure 5-11.

Air bag-Neck Interaction Mode 1

In the first air bag-neck interaction mode, the air bag directly loads the head (Figure 2), leading to a flexion moment at the neck. The neck shear is positive (Figure 5), which implies that the head is pushed rearwards relative to the neck, as a result of membrane tension. The head external shear is in the anterior-posterior direction (Figure 6) confirming the rearward pressure on the head by the air bag. The neck axial force is insignificant in magnitude and changes from compression to tension (Figure 7). The head external axial force is of small magnitude in the superior-inferior direction (Figure 8). The applied external loads are both larger than the corresponding neck forces. This indicates that, in this head/neck loading-pattern, the neck loads are primarily from the air bag loading of the head with only small loads of the air bag directly on the neck. The upper neck moment is in pure flexion (Figure 9), which is an indication that the center of air bag pressure on the dummy's head is beneath the CG of the head. The torso is accelerated rearward by the deploying air bag (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., [6] for Hybrid III 5th percentile female dummy (Figure 12). In this mode of air bag-neck interaction (Case 1, Figure 12), the moment-rotation relationship falls outside the corridor almost immediately after the head rotation starts, indicating that significant neck-moments can occur with little head rotation. The combined upper (Figure 9) and lower neck bending moments (Figure 11) cause the neck to flex into a reflected S-shape in second mode bending.

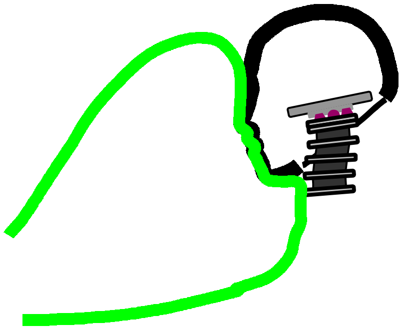

Figure 2. Air bag Loading the Head Directly

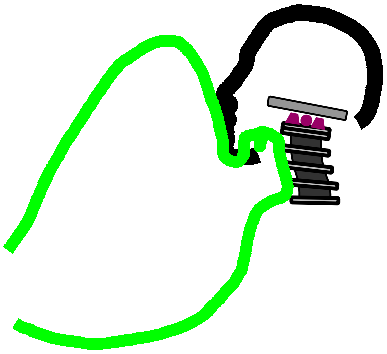

Figure 3. Air bag Trapped in the Chin-Jaw Cavity

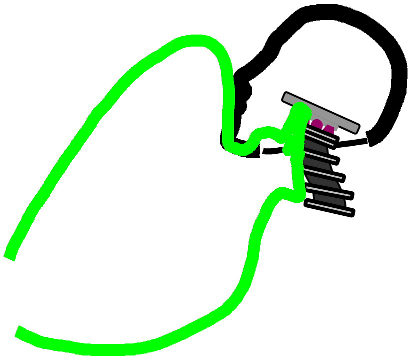

Figure 4. Air bag Trapped behind the Jaw

Air bag-Neck Interaction Mode 2

In the second air bag-neck interaction mode, the air bag contacts the head under the chin (Figure 3). The bag is trapped under the chin during the deployment. The neck shear changes to negative (Figure 5), which implies that the head is pulled forward relative to the neck shortly after the initiation of the air bag-dummy interaction and membrane tension has developed. However, the head external shear is insignificant in magnitude and changes direction from anterior-posterior in the beginning to posterior-anterior in the latter part (Figure 6). This implies that a major portion of neck shear comes from the inertial loading of the head on the neck, the direct loading of the air bag on the neck, or a combination of both. Significant tension load is present in the neck (Figure 7). The head external axial force is in the inferior-superior direction (Figure 8) and causes the head to pull on the neck. 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 pure extension in nature (Figure 9). The chest acceleration is mainly in the rearward direction (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., [7] (Figure 12, Case 2). The test data again falls outside the corridor, even at very small head-rotation angles. 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-shape seen in air bag-neck interaction Mode 1 (according to the moments in Figures 9, 11).

Air bag-Neck Interaction Mode 3

In the third air bag-neck interaction mode, the air bag contacts the head below the chin (Figure 4). 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 and membrane tension develops. The air bag pulls the head forward and upward, possibly pushing on the neck at the same time. The resulting neck shear is negative to a higher degree than in Mode 2 (Figure 5), which implies that the head is pulled forward relative to the neck. The head external shear maintains the posterior-anterior direction (Figure 6) during the whole event confirming the forward pulling of the head. 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. This could be due, either to the membrane tension in the deploying air bag in front of the dummy, pulling on the air bag material, trapped in the jaw-neck cavity, or the pressure of the trapped air bag material pushing against the neck and the jaw, or both. Tension is evident in the neck (Figure 7)

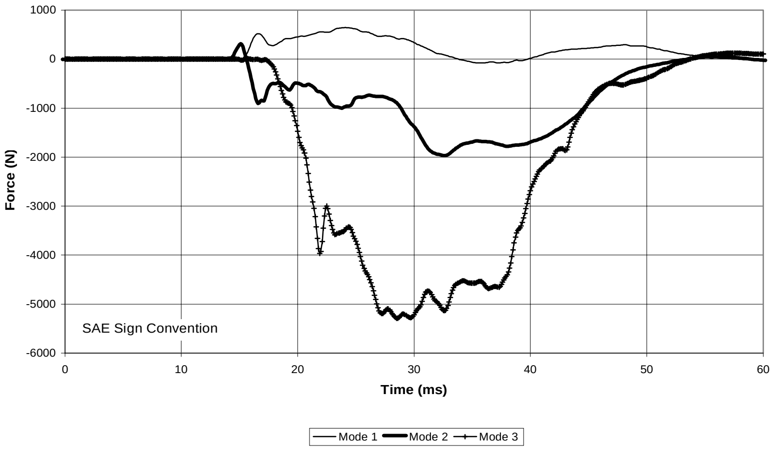

Figure 5. Upper Neck Shear Force.

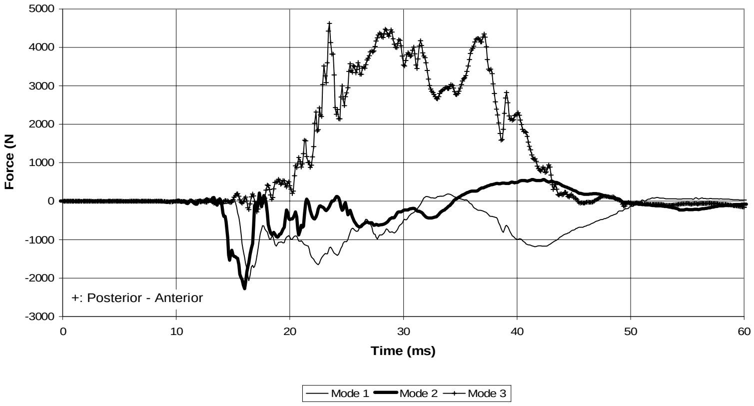

Figure 6. Head External Shear Force.

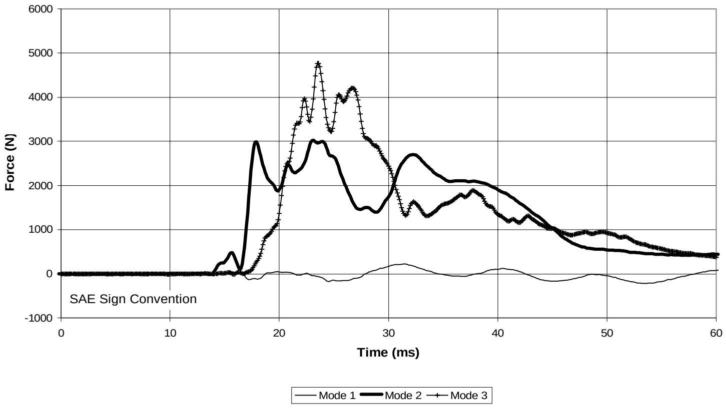

Figure 7. Upper Neck Axial Force.

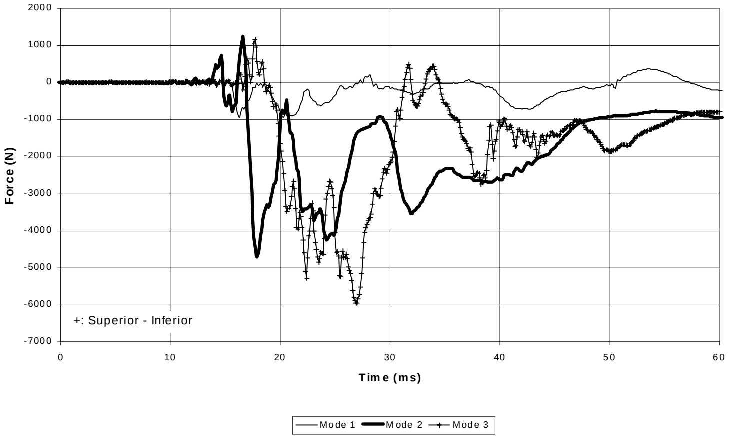

Figure 8. Head External Axial Force

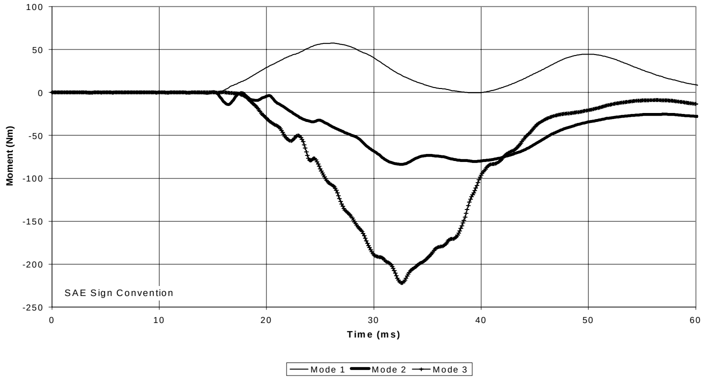

Figure 9. Upper Neck Bending Moment.

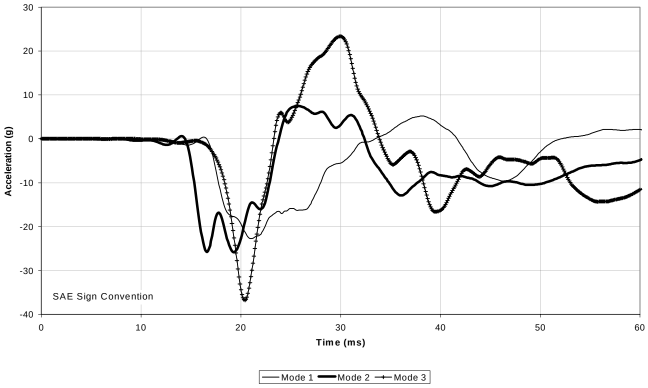

Figure 10. Chest X Acceleration.

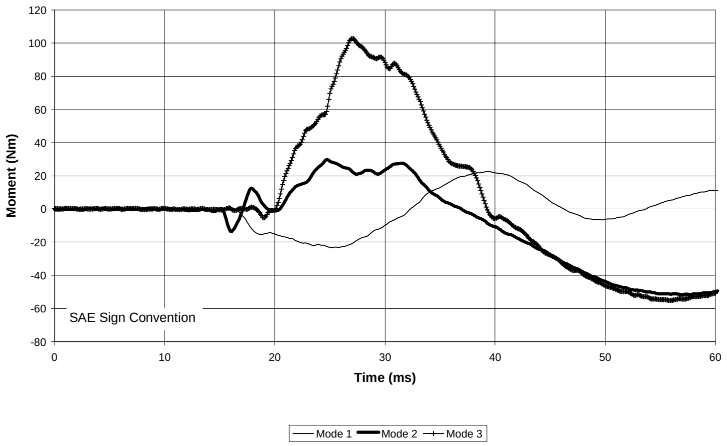

Figure 11. Lower Neck Bending Moment.

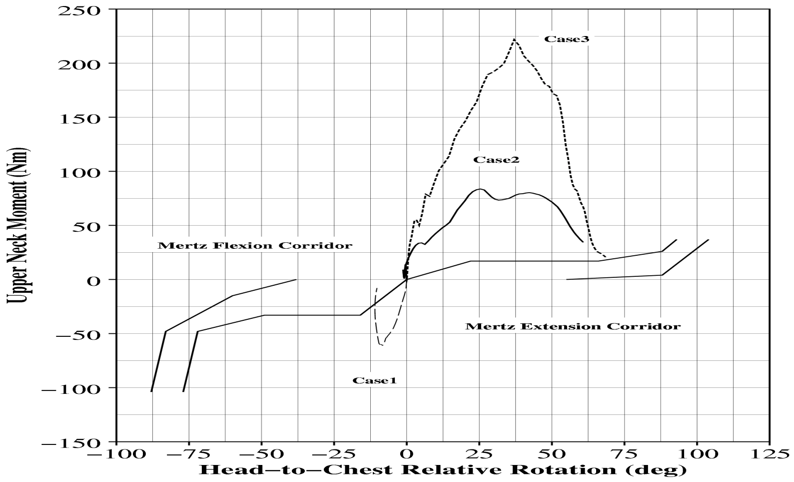

Figure 12. Upper Neck Moment vs. Head-to-Chest Rotation.

The head external axial force is in the inferior-superior direction (Figure 8) pushing the head 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 extension in nature (Figure 9). The chest acceleration changes from the anterior-posterior direction to the posterior-anterior direction (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 12, Case 3). The observed response falls outside the corridor starting with very small values of rotation. 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 neck deforms into S-shape, similar to air bag-neck interaction Mode 2, but with a larger curvature. The upper and the lower neck load cell moment outputs confirm this (Figures 9, 11)

DISCUSSION

The flexion and extension response corridors developed by Mertz and Patrick [3], and Mertz et al [6] are the primary basis for biofidelity of Hybrid III dummy's neck. The human volunteers, whose response was used to devise these extension corridors all have some degree of neck tension. Some tension is due to normal muscle activity holding the head in place. Additional tension could result from anticipation of impact. Under conditions of no neck tension i.e. cadaver response, the head would be expected to translate (due to inertial loading of the head) before showing significant rotation. The Hybrid III dummy neck is designed to deform in first mode bending in order for the moment-rotation curves to remain for the most part within the corridors. 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 5th percentile female is 2.06 Nm/degree for flexion and 0.77 Nm/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 action of 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. By basing the design of the Hybrid III dummy neck on corridors restricted to first mode bending, it is not clear if the dummy's head/neck response in case of loading by the air bag is biofidelic or not.

The three air bag-neck interaction modes observed with the Hybrid III dummy showed second bending mode response. In all the three cases the neck-moment versus head-rotation curves go out of the Mertz et al [6] corridors as soon as the head starts rotating, and never return, indicating that the dummy's neck is undergoing deformations which it is not conceived for.

The occurrence of the second bending mode in the human neck would seem likely in case of compressive loading of the human neck. However, when the air bag applies tensile forces in the neck by applying upward load to the chin-jaw region, a second mode bending seems unlikely because, the tensile load could be resisted only by aligning the muscle pairs with the direction of the load or engaging the ligamentous structure between the head and neck. Such an alignment could happen only after a substantial rotation of the head has occurred by which time the air bag would escape from under the human chin-jaw region.

Further, 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 [7,8]. Whereas, the current Hybrid III neck exhibits considerable bending resistance at its occipital condyle joint. This lack of compliance may allow large moments to be transmitted to the dummy's neck by the head without significant relative motion. In a human subject, motion and resistance to motion 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 axial and joint rotational stiffness on measured moments in the Hybrid III dummy during air bag loading using MADYMO occupant simulations. They found that decreasing the rotational stiffness had a dramatic effect on the extension moment.

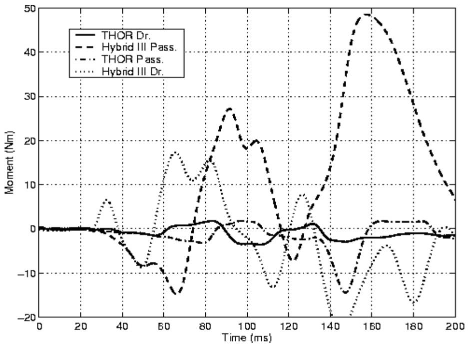

Figure 15. Neck Moment Comparison of THOR Dummy and Hybrid III Dummy [10

The Hybrid III dummy response appears to capture the global moment and head motion correctly in the first bending mode due to the use of the nodding blocks in the head-neck interface. However there is no way of estimating the local moment at the occypital condyles, equivalent to that which would occur in a human. By comparison, the NHTSA advanced dummy, THOR, has a neck system in which the loads on the head are resisted by the combination of a cable system and a beam like neck structure. Consequently, substantial head rotation is possible with relatively low 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 15). 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 eliminate the effect associated with the air bag trapping under the chin or behind the jaw, two experimental neck shield schemes were investigated [3]. The details of these investigations were presented in Ref.3. Essentially it was possible to eliminate the occurrence of both air bag-neck interaction Modes 2 and 3 with one neck shield design, and selectively eliminate only interaction Mode 3 with another neck shield design. In general, it appears that purely with neck shield designs although some level of control can be exercised on the neck-air bag artifact, the problem of passing the neck calibration tests and the problem of interference with the neck load cell measurement are faced.

CONCLUDING REMARKS

The artifact related to the Hybrid III dummy neck-air bag interaction manifests itself as the occurrence of second bending mode of neck deformation, which does not appear to be biofidelic.

Several approaches could be used to solve the problem of the dummy neck artifact. One way would be to design a suitable neck shield, which would prevent the air bag from entering the neck-chin-jaw cavity, and prevent the second bending mode of the neck deformation from occurring. However, in order for the neck shield to be effective, it may require a design that may not pass the calibration tests. In addition it may provide a bypass for a part of the load that should be measured by the load cell. In other words, although a neck shield would seem like a simple solution to the problem, developing a robust one is difficult.

Even if it were possible to come up with an efficient neck shield design, it would need a considerable extent of time before the neck shield would be an accepted part of the testing procedures. A large number of tests will have to be run by several organizations in order to establish confidence in the neck shield. This would be an effort of very significant extent.

In order for a neck shield design to be effective in all situations, it might become imperative to influence the basic response of the dummy head/neck complex by redesigning the basic neck components. In other words, a mixed approach, with a modified neck and a neck shield may become eventually necessary. This would be a very substantial work in itself followed by all the testing by several organizations before it is accepted widely.

A radical solution, in which the head/neck response could be made considerably more biofidelic would be by developing a dual load path system. The system would have a weak central bending structure, representing the vertebrae, and a strong 3D outer cable truss system, representing the muscle pairs. This would be the most time-consuming approach. The Hybrid III dummy has been known for a long time. A lot of experience has been gained with Hybrid III by the safety testing organizations all over the world. With the new system, it will take several years of testing before all the associated problems will be known, and solutions for them could be found.

Further, in order to design a more biofidelic head/neck system, a great deal of research into the human neck-airbag interaction will have to be carried out. At this time there is an acute shortage of biomechanics research results relating air bag deployment and human response. This is an effort, which will have to be carried out before reliable and robust biofidelic dummy neck systems can be produced.

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