TEST PROGRAM TO DEFINE OBLIQUE CHEST LOADING IN SIDE IMPACT

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Paper No. 09-0557

ABSTRACT

Near side impact crashes – especially pole impacts – have the potential to induce antero-lateral oblique loads to the chest. Current side impact dummies and most laboratory experimental studies have been designed to assess direct lateral impacts. A recent analysis of real world crashes indicated that the human chest experiences oblique loading in side impact crashes – in particular crashes into narrow objects. This paper describes the development of a new sled test program to determine the oblique impact response of the human and to evaluate dummy biofidelity in an oblique mode of loading. The program involves the use of chestbands on dummies in full-scale vehicle tests accompanied by sled tests with unembalmed post mortem human subjects (PMHS). Sled tests are run under varying load wall conditions with a buck configured specially to mimic dummy loading seen in the vehicle tests. The chestbands provide comparative measures of thoracic deformation. Ultimately, the chestband measures will help establish the instrumentation requirements of an ATD for use in a side impact test with a significant oblique component. Additionally, this work could help introduce more biofidelic injury metrics for side impact ATDs.

INTRODUCTION

Side impact crashes often produce more serious injuries and a higher percentage of fatalities than frontal crashes despite a lower overall incidence rate (NHTSA Traffic Safety Facts, 2007). Vehicle to vehicle configurations as well as single vehicle crashes are common. Current federal motor vehicle safety standards address both of these crash types. Most single vehicle side crashes result when the driver loses control and collides with a fixed object. Often the fixed object is a pole or tree. A study using US DOT National Automotive Sampling System (NASS) and Fatality Analysis Reporting System (FARS) data indicated that the overall distribution by crash delta-V of vehicle-to-vehicle side impacts was approximately equal to narrow object impacts (Zaouk et al, 2001).

A more recent investigation of the NHTSA Crash Injury Research Engineering Network (CIREN) database examined side pole crashes in more detail. The CIREN data was used to determine injury mechanisms and associated injuries related to the pole impact location on the vehicle. It was determined that the most devastating injury patterns occurred when the center of the pole impact was between the center of the wheelbase and 25 cm forward of the center of the wheelbase (Figure 1) (Pintar, et al, AAAM, 2007). For this location of maximum damage, greater than 60% of occupants sustained AIS 3+ injuries to head, chest, and pelvis body regions. This particular location was also responsible for a unique chest injury pattern that produced unilateral rib fractures and lung contusions. It was hypothesized that this injury pattern was induced by oblique loads to the chest through the intruding door wherein the center of the intrusion was slightly forward of the occupant torso.

PURPOSE

Since the findings from the CIREN study on narrow object side impacts indicated that the most devastating injuries were sustained with a pole impact to a certain small area of the vehicle, this type of impact was investigated in more detail. The CIREN study concluded that because the chest injuries in these occupants were largely unilateral (closest to impact), and due to the shape of the door intrusion profile, the intruding door induced an oblique load to the antero-lateral portion of the occupant’s chest. This was also verified in many vehicles by twisted seatbacks indicating asymmetric loading.
This hypothesis is being pursued in the testing program described herein. The desire is to replicate the real world loading conditions in a laboratory sled test procedure. The real world results are first reproduced in full-vehicle side pole crash tests. Injury patterns in the vehicle crash test are then verified for similarity with those found in the CIREN study occupants.

Thereafter, the loading mechanisms can be defined in more detail. The chestband instrumentation is used to describe the magnitude and shape of oblique chest loading. Accelerometer signals from different parts of the torso are used to define the relative timing of the loading to the body regions. The goal of the sled test protocol is to replicate the shape of the chestband contours and the relative timing of the body region loads observed in the vehicle crash tests.

The ultimate goal of the test program is to use the sled test protocol to conduct multiple tests defining injury metrics for oblique chest loading and dummy biofidelity response requirements (Table 1). The sled test protocol is desirable because it provides a well-defined, highly repeatable environment in which specialized instrumentation may be applied to fully evaluate biomechanical response and injury tolerance. This paper describes how the full vehicle crash tests are used to develop the sled testing protocol.

METHODS

The initial methodology for the two experimental test series – the full-vehicle tests and the sled tests – is described below. Preliminary results are given to provide data being used to generate final protocols.

To determine the degree of oblique loading to the chest, a series of full-scale vehicle tests with both ATDs and PMHS have been conducted. Using passenger cars and sport-utility vehicles (SUV), tests have been carried out to observe the pattern of oblique loads in an actual vehicle environment. These tests define the temporal thorax deformations through the use of chestbands. The crash tests also define the relative timing between shoulder, thorax, abdomen, and pelvis during the impacting event. A sled buck has been designed with angled load plates that induced antero-lateral oblique loads to the occupant similar to those seen in the vehicle tests.

Subjects. All tests are carried out with post mortem human subjects (PMHS) and with different types of dummies. In accordance with standards set forth by MCW's Institutional Review Board, unembalmed PMHS are procured, medical records evaluated, and screened for HIV, and Hepatitis A, B, and C. Anthropomorphic data and pretest x-rays are obtained and chestbands are affixed according to procedures established by (Pintar et al., 1997). Specimens are dressed in tight-fitting leotards, and a mask covers the head/face.
Table 1. Relationships between studies that define entire program.

<table>
<thead>
<tr>
<th>Type of Study</th>
<th>Purpose</th>
<th>Outcome</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>53 CIREN Occupants in narrow-object side impacts</td>
<td>Define real world injury patterns</td>
<td>Location for damage corresponding to worst case injury pattern</td>
<td>Need relative timing for different types of vehicles</td>
</tr>
<tr>
<td>Full-Vehicle Crash tests with PMHS</td>
<td>Reproduce damage and trauma at location defined in CIREN cases.</td>
<td>PMHS provides injury pattern, relative timing of body regions loaded, and chest deformation patterns</td>
<td></td>
</tr>
<tr>
<td>Sled tests with PMHS and Dummy occupants</td>
<td>Reproduce vehicle crash test chest deformation patterns and relative timing of loading to body regions.</td>
<td>Biofidelity requirements and injury criteria for oblique side impact loading</td>
<td>Design load wall to match loading conditions seen in vehicle crash</td>
</tr>
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</table>

The PMHS are examined for injury with a complete autopsy following the test. Anthropomorphic test devices (ATD) or dummies, are also used. ATDs are being used to conduct preliminary evaluations of sled buck design to ensure that the goals of the design are being met. It is important to conduct matching tests with ATDs to determine if the sled buck design and overall test protocol are producing consistent results. For example, an obliquely oriented load wall has been evaluated by varying the angles of impact, and the timing of contact between thorax, abdomen, and pelvis have been evaluated by varying the extent of pelvic plate offset. ATDs provide a consistent, repeatable output to determine if sled changes have an effect. In this way, PMHS tests are only completed after the protocol has been validated with ATDs.

**Subject Instrumentation.** In all tests, a standard set of instrumentation is used. Each of the human surrogates is instrumented with head, T1, T12, and sacrum triaxial accelerometer packages (Figure 2). In addition, a nine-accelerometer package (NAP) is used to derive head angular accelerations. For the dummies, an internal NAP system from the dummy manufacturer is used, and for the PMHS, a custom-designed pyramid NAP (PNAP) is mounted as described and validated previously (Yoganandan et al., 2006). Rib and sternum accelerometers are also mounted directly to the subject.

Each surrogate is instrumented with a 59-channel chestband device to record chest deflection contours. Each chestband uses 59 strain gauge bridges located around the band to measure the local curvature; curvatures are interpreted and combined over the length of the band at a given time point to produce a total contour of the chest. The contours are computed throughout the event to capture chest shape change. Local deformation at any point along the contour can be calculated with respect to a reference point.

![Subject Instrumentation](image)

**Figure 2:** Each PMHS and dummy was instrumented with triaxial accelerometer packages (squares) at the head, T1, T12, and sacrum. In addition, a nine-accelerometer package (triangle) was fixed to the head to derive angular accelerations. Chestbands were also included to determine the nature of the oblique loads to the thorax.

**Fitting subjects with Chestband:** Since the internal ATD instrumentation is uni-lateral and measures only one location per rib level, matched-pair tests conducted using ATDs are also instrumented with chestbands (Figure 3). On the PMHS, the chestband
is placed just under the axilla such that rib-4 laterally is directly under the chestband; on the dummies the chestband is placed over the upper rib (Pintar et al., 1997).

The accelerometers at T1, T12, and pelvis are triaxial and are used to determine relative timing of the sequence of loading that occurs to the upper thorax, abdomen, and pelvis. To secure the triaxial packages to the PMHS, custom designed mounting blocks that allow for screws into the lamina or pedicle of the vertebrae are used. The rise time of each of the y-axis accelerometer responses is used to assess the time at which each body segment is loaded by the sled plates. This same instrumentation package is used in both the full-vehicle tests and the sled tests so comparisons can be made.

Customized software has been written to provide flexibility in choosing where to measure the chest deformations. The custom software also allows a choice of reference points so that chestband deformations can be compared to dummy internal deflection sensor measures. A series of contours can be animated to show the change in deformation throughout the test. The chestband is a versatile research tool that provides direct measures of chest deflection in both PMHS and ATDs. It provides the best known method of relating chest deformations and patterns with injury in the PMHS. This, in turn, can be used to derive injury criteria for specific ATDs as the same measures in matched-pair tests can be used to equate injury risk to a biomechanical metric.

Figure 3: ES-2re dummy thorax fitted with a chestband over each of the three ribs.

Processing of Chestband Contour Data. To examine the chestband contour results, the data is processed using RbandPC software and customized post-processing software developed in-house as follows. First, contours are calculated at every millisecond from chestband curvature signals using RBandPC software (Version 3.0, Conrad Technologies Incorporated, Washington, DC, USA, available from NHTSA) and pretest measurements of the specimen (Pintar et al., 1996). The local coordinate system is defined by using the two gauges closest to the posterior tip of the spinous process at the appropriate level of the thorax. Gauges closest to the spinous process, sternum, and the most lateral points on the left and right sides of the specimen are identified by palpation and recorded, including measurements of left to right chest breadth and sternum to spinous process depth.

On each contour, one-half of the chest deflection is computed. The origin is identified at each contour time step by determining the point one-half the chest breadth distance from the spine along a vector from the spine to the sternum. Distances from each point on the contour to the origin are computed at every time step, and the initial length is defined as the distance in the pre-test contour (approximately 100 milliseconds before impact). The maximum deflection is computed by finding the point on the contour which yields the greatest change from its initial length (Figure 4).

Figure 4: Chestband Contour Plots depicting location of maximum deflection (Black/Blue arrows) and location where deflection would mimic a dummy internal sensor (red arrows).

This method, called the “forced-angle” response, is slightly different than what has been used in the past (Maltese, et al 2002). Previous methods calculated deformations along a line perpendicular to the center
line between spine and sternum. The forced-angle method uses a fixed point of reference just as a dummy chest deflection measurement device is anchored at a fixed point at the spine box. From this fixed reference point one can force an angle (90 degrees) to mimic how an ATD would measure the deformation, or one can allow the algorithm to pick the angle at which the maximum deformation occurs. This permits either direct comparison with dummy internal measures or defines the location where the maximum deflection could be detected if an internal measurement device would be appropriately located.

Full-Scale Vehicle Tests

Full-scale vehicle crash tests have been conducted at 32 km/h into a 10-inch diameter pole. The test matrix is indicated in Table 2. The goal of this test series is to reproduce similar injury patterns to those seen in the real-world CIREN cases (i.e., skull fractures, unilateral (left) rib fractures, and a pelvis or lower limb fractures.) Additionally, these tests are used to establish the relative timing of body segment contact for different types of vehicles and to see if the timing is appreciably different between vehicle types. The ES-2re and the NHTSA-SID-H3 dummy are being used to help define the relative timing of body segments more clearly between vehicle types and to serve as a verification of the PMHS testing.

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Occ. type</th>
<th>Speed (km/h)</th>
<th>Test conducted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small Car</td>
<td>PMHS</td>
<td>32</td>
<td>To be completed</td>
</tr>
<tr>
<td>Small Car</td>
<td>ES-2re</td>
<td>32</td>
<td>1996 Merc Mystique</td>
</tr>
<tr>
<td>Small Car</td>
<td>SID-H3</td>
<td>32</td>
<td>1994 Toyota Corolla</td>
</tr>
<tr>
<td>Mid-size Car</td>
<td>PMHS</td>
<td>32</td>
<td>1993 Dodge Intrepid</td>
</tr>
<tr>
<td>Mid-size Car</td>
<td>ES-2re</td>
<td>32</td>
<td>1990 Audi 100</td>
</tr>
<tr>
<td>Mid-size Car</td>
<td>SID-H3</td>
<td>32</td>
<td>1999 Ford Taurus</td>
</tr>
<tr>
<td>SUV</td>
<td>PMHS</td>
<td>32</td>
<td>1995 Jeep Cherokee</td>
</tr>
<tr>
<td>SUV</td>
<td>ES-2re</td>
<td>32</td>
<td>1989 Jeep Cherokee</td>
</tr>
<tr>
<td>SUV</td>
<td>SID-H3</td>
<td>32</td>
<td>To be completed</td>
</tr>
</tbody>
</table>

With respect to the occupant, this location was translated as the center of the pole aligned with a point 10 cm forward of the occupant H-point. The vehicles chosen to this point for testing have been those available from the local discard lot that did not have any structural anomalies. The vehicles did not have side airbag systems which helped to better distinguish the timing of when the occupant contacted the intruding door with different portions of the body.

In tests conducted thus far, the principal direction of force was 285 degrees, or 15 degrees off a direct 9 o’clock impact to the driver. The vehicles were instrumented with a tri-axial center of gravity (CG) accelerometer and door accelerometers in front and rear aspects recording in the lateral direction.

Sled Tests

The sled buck design is being used that allows for direct experimental investigations into human injury criteria that may differ from existing direct lateral injury criteria. It also allows for matched-pair testing of PMHS and ATDs to obtain biofidelity criteria and assess dummy responses. Such a sled buck is intended to be generic enough not to represent a particular vehicle and yet produces the type of loading environment that the human experiences in the actual crash environment. The sled buck design should also demonstrate experimental repeatability and be easily reproduced in computational modeling studies.

Previous Sled Configuration. In the past, a high degree of success has been achieved experimentally by defining the near side impact pulse as primarily a change in velocity between the door and the occupant (Kalieris, original Heidelberg setup, Pintar Stapp side impact, Maltese, et al, 2002). Thus, a generic rigid wall was designed in these early experiments to mimic the average overall dimensions of a vehicle door but to also facilitate load wall sensors defining loading to various body regions. The results of using this load wall arrangement facilitated injury criteria development including the Thoracic Trauma Index (TTI) and maximum chest compression (Cmax) as injury indicators in dummies used in regulatory tests. Such a sled design has also been amenable to assessing the effects of padding and even offers the inclusion of airbag technology.

Initial Sled Configuration. The first attempt at a sled buck design was to alter the previous configuration to incorporate an oblique loading vector to the chest.
The design included a Teflon-covered seat and minimally supported back such that the occupant would slide across the seat during the application of the sled pulse and would contact the rigid wall at the predefined velocity setting. This laboratory sled buck was designed with the intention of matching the full-vehicle test results as closely as possible. The main goal of the initial design was to mimic the relative timing of body contact with the load wall (vehicle door).

Using the full-scale vehicle test data as a reference, the onset of acceleration in the direction of sled travel (Y-axis) for T1 (thorax), T12 (abdomen), and sacrum (pelvis) accelerometers was assessed. The sled load wall design was initially selected to match the previous design used during 90º side loading evaluations of the various side impact ATDs described earlier (Maltese et al., 2002; Yoganandan et al., 2002). The load wall is composed of four distinct load plates: one each at levels of the subject’s thorax, abdomen, pelvis and legs. Force transducers on the plates measure loads imposed by the test subject. The load plates may all be fixed along the same vertical plane, or one may be positioned closer to the subject (and offset from the other plates) so that it bears more of the initial load.

In the 15º full-vehicle pole tests, it was observed that the door intrusion and subject position produced a door-to-subject interaction angle that was actually sharper than 15º. Thus, the original test setup has been modified so that the upper (thorax) and middle (abdomen) load plates contact the test subject obliquely (i.e., the load vector has both lateral and frontal components) rather than strictly laterally as in previous tests (Figure 5).

The desired effect is achieved by positioning individual load plates at angles relative to the deceleration vector. The pelvic load plate is not angled to allow the lower limbs to move freely in the vector direction. It is felt that if the pelvic plate is angled there will be the potential to induce an artificial fulcrum point which would not only induce trauma to the occupant, but also alter the body motion of the upper torso.

The load plates are also offset from each other such that contact timing with body segments may be altered. To date, a series of ATD and PMHS sled tests have been performed using various load wall set-ups to mimic the range of oblique loading experienced in actual full-scale vehicle tests. Once the testing is complete, the results of the PMHS and ATD tests will be compared to examine the biofidelity of the ATD thorax under oblique loading.

**RESULTS**

**Full-Vehicle Pole Tests.** To date, two PMHS have been completed in full-vehicle crash tests; one in a mid-size car and another in an SUV. Analysis of the video from the experiments demonstrated that as the pole deformed the vehicle, the body continues moving in the direction of travel. As the door deformation proceeded, the focal intrusion just anterior to the occupant torso produced an angular intrusion and loading on to the anterolateral area of the chest. It appeared that the chest was loaded by the intruding door and squeezed into the seatback.

The autopsy results indicated that both PMHS had a skull fracture; accelerometer traces demonstrated head contact with the pole. Each PMHS also had extensive left sided rib fractures as well as lower limb trauma (Table 3). With just these two PMHS it was demonstrated that the trauma produced in these crash tests was very similar to the trauma recorded in the real world CIREN cases where the pole intrusion was in the same location on the vehicle. There was AIS=3+ trauma in head, chest, and pelvis or lower extremity regions.

The experiments demonstrated that the chest in this crash configuration does experience oblique loading. The chestband contours demonstrated that the anterolateral aspect of the thorax was loaded so severely that the chestband experienced a kink as the PMHS was squeezed between the door and the seatback (Figure 6).
Table 3. Injuries documented in the PMHS tests in full-vehicle crashes.

<table>
<thead>
<tr>
<th>Test Configuration</th>
<th>Head Injury</th>
<th>Thorax Injury</th>
<th>Pelvis/Lower Extremity Injury</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMHS in Mid-Size Car</td>
<td>Left zygoma and Basilar skull fractures MAIS=3</td>
<td>&gt; 3 rib fractures left side and zygoma fracture MAIS=3</td>
<td>Displaced/comminuted left femur, pelvic ramus fracture MAIS=3</td>
</tr>
<tr>
<td>PMHS in SUV</td>
<td>Bilateral orbital wall fractures, linear and Basilar skull fractures MAIS=3</td>
<td>&gt; 3 rib fractures left side with flail chest, zygoma fracture MAIS=4</td>
<td>Pubic symphasis, sacroiliac joint, unstable rami fractures MAIS=3</td>
</tr>
</tbody>
</table>

Figure 6: Chestband contour of PMHS in full-vehicle side pole impact test.

Sled Tests. PMHS tests have been completed with both 30 and 20 degree angled plates. Examples of chestband contours from PMHS tests run in both configurations are demonstrated in Figure 7. From these results it appears that the 30 degree load wall configuration mimics the chestband contour shapes and location of maximum deflection from the full-vehicle test configuration slightly better than the 20 degree sled test.

In order to address the question of body segment timing, the measures from the Y-axis accelerometers at T1, T12, and pelvis have been examined. The 30-degree load wall on the sled was adjusted such that the offset distance between the thorax and abdomen plates compared to the pelvis and leg plates was 5 cm, 7.5 cm, or 10 cm. The NHTSA-SID dummy was tested in all three configurations and compared to a full-scale vehicle test run also with the NHTSA-SID.

The body accelerations of all four of these tests are compared in Figure 8. As far as the timing of the signals, it is apparent that the 5 cm sled test comes closest to the timing in the vehicle test. The accelerometer signals from two PMHS full-vehicle tests are shown in Figure 9. It is apparent from these traces that the relative timing of the body segments in the full-vehicle pole test is such that the pelvis is contacted first with the torso lagging somewhat.

DISCUSSION

A test program to characterize the extent of oblique loading in side impact is being established. From the examination and analysis of more than 50 CIREN real world cases it is hypothesized that oblique chest loading occurs in side pole crashes when the pole impact site is just forward of the occupant torso. This scenario produces severe head, chest and lower extremity injuries and is characterized by unilateral rib fracture patterns and lung contusions. This scenario is reproduced in a laboratory setting by orienting the center of the pole 10 cm forward of the H-point of the occupant. Chestband contours document the extent of oblique chest loading in PMHS occupants.

Using the full-vehicle tests as a guide, a unique sled test has been designed to mimic the oblique chest loading. A series of PMHS and dummy tests have revealed that a 30 degree oblique load to the thorax and abdomen of the occupant, offset by about 5 cm from the pelvis and leg load wall reproduces the relative timing of body segment loading. These settings will be further verified in future experiments with additional dummies and PMHS.

It is also apparent that because human anthropometry varies considerably, the sled load wall plates should be designed to adjust to such variations. In other words, a fixed thorax plate on the sled may impact one PMHS at the rib-5 level and a second PMHS at the rib-2 level. The future design of the load plates will take into account such variations in PMHS anthropometry so that direct comparisons of shoulder, thorax, abdomen, and pelvic loads can be made between dummies of different sizes and PMHS of different sizes.
Figure 7. PMHS chestband contours from 20-degree (left) and 30-degree (right) sled tests. Note that direction of maximum deflection is closer to vehicle test (figure 6) for 30-degree tests than for 20-degree tests.

Figure 8. Accelerometer Y-axis traces from a SID-H3 dummy run in a full-vehicle pole test (up-left), 5 cm offset sled test (lo-left), 7.5 cm offset sled test (up-right), and 10 cm offset sled test (lo-right). Note the relative timing of the acceleration signals is most similar between the pole test and the 5 cm offset sled test.
Figure 13: Accelerometer Y-axis traces from PMHS runs in full-vehicle pole tests.

In future efforts, the degree of oblique loading in full-scale vehicle tests and in subsequent sled tests will be further characterized using the chestband contours. These contours can be used in conjunction with the “slice” model to identify the minimum number of chestband points (and their locations) that are needed to sufficiently characterize thorax deformation as described in Campbell et al, 2005. In this manner, the “slice” model may be used to assess ATD instrumentation requirements for measuring oblique thorax loads. The model also provides many valuable insights used in the design, development, and evaluation of restraint systems. And in a sufficiently biofidelic and properly instrumented ATD, the “slice” measurements, which include measures of stress and strain, can conceivably be used as a means to assess injury potential.

The configuration of the tests described earlier represents a worst-case scenario. The level of oblique loading seen in other types of full-scale vehicle crash tests is probably lower than that prescribed herein. Nonetheless, it may be used as a benchmark for ATD use in any sort of developmental tests where the oblique component rises beyond those seen in actual full-scale vehicle crash tests. Under oblique loads such as those imposed by the 30-degree load wall, it is likely that additional ATD measurement locations will need to be monitored in order to accurately record the oblique loading response. Development of such a system for measuring dummy chest deflections in multiple locations optically is already on the market. The RibEye measurement system is currently being evaluated by the NHTSA as a potential improvement to dummy chest deflection measures.

Human injuries: oblique vs. lateral. Contents of the human thoracic ribcage and abdomen are complex, multifunctional, three-dimensional, and, from a biomechanical and material property perspective, heterogeneous. An oblique impact, at the same severity and to the same level of the chest, engages the same internal organ differently, compared to the pure lateral vector. For example, at the upper thoracic region, the pure lateral vector directly loads regions dorsal to the subclavian artery while an oblique vector at 30-degree applies impact forces to ventral arterial regions engaging the common carotid artery and brachiocephalic vein. The former vector introduces postero-anterior load transfer to these tissues, in contrast to anteroposterior load transfer by the oblique vector. The ribcage is loaded with direct compression at its most lateral region by the pure loading vector.

This is in contrast to the angulated compression at the anterolateral region by the oblique vector. The anterior regions of the thoracic vertebral body sustains lateral shear in the pure loading case, whereas it resists a force angled towards the right pedicle in the oblique case. At an inferior level, while the aorta is protected by the stomach in the pure lateral loading vector, in the oblique vector case, the major vessel is protected by the relatively smaller left lobe of the liver and its articulations (Yoganandan et al, 1996). Similar regional load transfer mechanisms are apparent as the impact vector traverses caudally. Purely anatomic considerations with respect to the impact vector in addition to functional and constitutive differences are responsible for the mechanisms of load transfer, tissue injury, and biomechanics (Yoganandan et al, 2000).
The direct 90 degree lateral loading on the struck side induce deformations of the ribcage initiating from the region of peak skeletal curvature. In contrast, an obliquely oriented vector induces antero-lateral compression of the ribcage on the struck side, and the impact force is thus transferred via a combined shear and compression mechanism at the initiating region. Frontal impact-induced chest injuries with belt-only versus combined airbag and belt loadings have used this type of concept for determining load transfer to the skeletal structures and soft tissues and delineating injury mechanisms (Pintar et al, 2007; Pintar et al, 2008). The added shear component in the oblique side impact vector places demand on soft tissue structures housed within the ribcage. The hoop tension resulting as a consequence of the compressive deformation on the antero-lateral region superimposed with the tangential component is the primary difference in the internal load-sharing mechanism between the two modes of impact. These factors may explain the more aggressive nature of the oblique than the pure lateral vector; a finding recently observed in cases examined by CIREN; narrow object and oblique impacts imparting more severe injuries than pure side impacts (Yoganandan et al, 2003; Yoganandan et al, 2008). This recent study reported that oblique impacts produced more unilateral fractures along with ipsilateral soft tissue trauma.

Anthropomorphic Test Devices. Several types of anthropometric test devices (ATDs) have been developed for use in standardized side impact testing. They include 50th percentile male versions of the EuroSID, the WorldSID, and the NHTSA-SID, and versions of the SID-IIs 5th percentile female dummy. While all four dummies are distinct from one another, they all provide calibrated responses to impacts from the near side. In each case, the dummy has a rib cage that consists of spring steel ribs of one form or another, and lateral displacement is measured by linear displacement transducers mounted between the ribcage and thoracic spine.

As an example of ATD instrumentation, consider a rib module of the ES-2 version of the EuroSID, shown in Figure 14. The ES-2 has three such thoracic rib modules, each with a linear slide and damper mounted inside a steel band. A single-degree-of-freedom potentiometer measures rib displacements. This instrumentation is typical of all four dummies in that they all measure rib displacement along a single axis.

Figure 14: ES-2 Rib Module

The problem of detecting oblique loads in an ATD may not require an exact knowledge of where the loading vector is directed. There are emerging deformation-sensing instrumentation systems that allow for multiple points of measurement. Unlike the chestband, which is secured to the outside of the torso, these systems allow for internal measures at multiple points and in multiple directions. The advanced THOR-NT has four different sensors called CRUX potentiometers that measure the X, Y, and Z-directions of motion of that point on the rib cage. The RibEye LED optical system measures two or three directions of movement of up to 12 locations mounted on the internal aspects of a dummy rib cage (Yoganandan et al, 2009 ESV). Although these systems are more complex than a single potentiometer and may require some degree of understanding of what to do with the output, they are potentially the solution to measurement of oblique chest loads in ATD. The results of the current test program will produce the necessary correlations between PMHS and dummy measures when the loading vector to the chest is from the anterolateral direction.

SUMMARY

This paper summarizes an ongoing plan of research designed to characterize human response in oblique side impacts. The goal of this work is to establish the degree of oblique thoracic loading within post-mortem human subjects and ATDs with the aim of determining differences and possible enhancements of available test dummies and injury criteria. This is accomplished through the use of a new sled test protocol with varying load walls in which human subjects and ATDs are fitted with chestbands to provide comparative measures of thoracic deformation. The chestband measures also help establish the instrumentation requirements of an ATD for use in a side impact test with a significant oblique component. Additionally, this work may help
Introduce more biofidelic injury metrics for side impact ATDs in oblique loading environments.

The goal of this work is to establish the degree of oblique loading and biofidelity responses in a side impact environment through the use of chestband contours, and sled tests with varying load walls. In addition, this research will help establish the instrumentation requirements of an ATD used in side impact tests that may have a significant oblique component.

ACKNOWLEDGEMENTS

This research was supported in part by the US DOT NHTSA cooperative research program DTNH22-07-H-00173 and by the Department of Veterans Affairs Research. We gratefully acknowledge Mark Meyer and the rest of the Neuroscience Research Laboratories staff in the conduct of the experiments.

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