SENSITIVITY OF THOR AND HYBRID III DUMMY UPPER AND LOWER NECK FORCES AND MOMENTS TO BELT SYSTEMS IN FRONTAL IMPACT

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ABSTRACT
The objective of the study was to determine the head-neck biomechanics with a focus on lower neck injury metrics using different anthropomorphic test devices (dummies). Specifically, sled tests were conducted by positioning the mid- and large-size Hybrid III and Thor dummies in a custom designed frontal impact buck that consisted of a rigid seat, an adjustable head restraint, and an adjustable knee bolster. Tests were conducted at low, medium, and high change in velocities using three restraint conditions. Peak upper neck moments were more sensitive than peak upper neck forces for all dummies. Moments in the Thor dummy were more sensitive than the moments in the mid-size Hybrid III dummy at both the upper and lower necks. This study offers restraint-based data and addresses biofidelity differences between dummies, and dummies of the same family with differing size. Such data are critical in off-center and small overlap frontal crashes where airbag may not offer the most optimum protection, and for rear seat occupants wherein frontal impact airbags do not exist.

Key Words: Sled tests, injuries, frontal impact, three-dimensional

DESPITE CONTINUAL CHANGES IN TECHNOLOGIES and increase in manual use of restraint systems in the United States, motor vehicle frontal impacts continue to dominate the injury spectrum, from fatalities and survivors. To assess trauma in these environments, laboratory-driven sled tests are commonly used (Yoganandan et al., 1998). Tests are conducted using PMHS and dummies to identify and document injuries, establish injury mechanisms, determine parameters to describe the biomechanics, evaluate the biofidelity of dummies, and develop injury criteria for different body regions. Sled tests have been conducted using unembalmed PMHS by the authors with a focus on thoracic injuries, and similar protocols have been used by researchers in Europe (Kallieris et al., 1982, Yoganandan et al., 1994, Yoganandan et al., 1991). Studies have led to the evaluation of the efficacy of certain injury metrics used in thoracic trauma assessments. For example, asymmetrical loading induced by three-point belts with or without the presence of frontal airbags have shown the inadequacy of the central chest deflection metric, measured in the world-wide used mid-size male Hybrid III dummy, to appropriately characterize thoracic trauma (Morgan et al., 1994). These efforts have served as a basis for measuring chest deflections using optical systems at different locations and along different axes, termed multi-point measures. Thoracic trauma assessments have received a significant majority of the focus. Another important body region in frontal impacts is the head, as brain injuries can have serious consequences. The neck of the dummy is the load delivery device for the head, and head-neck kinematics are primarily governed by the fore-aft rostral dorsal spine accelerations in the absence of head contact during the frontal impact loading event. Although researchers have attempted to measure biomechanical variables in the head-neck region, only the upper junction has been studied. Lower neck loads have not been systematically recorded and analyzed, although a load cell exists at this location in frontal impact dummies, including the Hybrid III family and Thor-NT. Acknowledging that this region of the cervical column sustains injuries to surviving occupants in frontal impacts and paucity of data, the objective of the study was to determine the head-neck biomechanics with a focus on neck injury metrics using different dummies.
METHODS
The frontal impact buck consisted of a rigid seat, an adjustable head restraint, and an adjustable knee bolster. The adjustable buck was designed to accommodate varying anthropometry of dummies to test different types of restraint systems with the same initial positioning. This was true for both the Hybrid III family of dummies and the THOR-NT (Thor) dummy. The knee bolster was covered with 30 psi paper honeycomb padding and was adjusted for each dummy by maintaining a 25-mm gap between the front of the knee/lower limb and honeycomb padding. The head restraint was adjusted such that the center of the restraint was slightly in contact with the most rearward region of the head of the dummy. Figure 1 shows the Hybrid III dummy seated on the buck of the sled. Tests were conducted using an acceleration sled (servo-sled, Seattle Safety Inc., Seattle, WA, USA). The overall test matrix included the mid- and large-size male Hybrid III dummies, and the mid-size Thor dummy. Tests were conducted at low (3.3 m/s), medium (6.7 m/s), and high (15.7 m/s) change in velocities using the three restraint conditions: normal three-point belt with no pre-tensioning (no PT); ten-centimeter pre tension (10cm PT); and two-hundred Newton pretension (200N PT). The upper and lower neck load cell data, nine accelerometer records from the sensors inside the head of the dummy, and T1 acceleration histories were used to determine the sensitivity of neck metrics (forces and moments) at the upper and lower regions to different types of belt systems. All accelerometer and load cell data were gathered according to SAE specifications. A 20-camera motion capture system (Vicon Inc., Oxford, UK) was used to track the head-neck kinematics in three-dimensional space. Cross-sectional loads in the Thor dummy were obtained to compare the responses with the Hybrid III dummy. Duplicate tests were conducted for each dummy and at each velocity. Sufficient time was allowed to lapse between two consecutive tests. Results are provided to evaluate the sensitivity of upper and lower neck metrics to different dummies and dummy designs at different velocities.

RESULTS
The morphology of time histories of head linear and angular accelerations, and forces and moments at the upper and lower necks were similar for all dummies although the times of attainments of peaks were not identical. Typical plots of lower neck moment-time histories are included in figure 2. Forces and moments at the upper and lower necks for all dummies at all velocities were normalized with respect to data from the normal three-point belt with no pre-tension (Figures 3 and 4).

Figure 1: The mid-size Hybrid III dummy seated on the buck of the sled.

Figure 2: Lower neck moment in the Thor (left) and mid-size Hybrid III dummies. Duplicate tests were done under each restraint condition (re: no PT, green: 10cm PT, and blue: 200N PT).
Figure 3: Ratios of forces (left column) and moments (right column) at the upper neck for the three restraints in the Hybrid III mid-size (red) and large-size (blue), and Thor (green) dummies. Top, middle, and bottom rows correspond to data from the low, medium, and high change in velocities. See Results section for details.

Figure 4: Ratios of force (left column) and moments (right column) at the lower neck for the three restraints in the Hybrid III mid-size (red) and large-size (blue), and Thor (green) dummies. Top, middle, and bottom rows correspond to data from the low, medium, and high change in velocities. See Results section for details.
DISCUSSION
Recent changes in restraint systems include pre-tensioners and load-limiters. These features induce varying head-neck kinematics depending on factors such as change in velocity and anthropometry. Varying kinematics results in altered neck loads. While upper neck loads are used in the Nij criterion for crashworthiness assessments in the United States, its sensitivity to differentiate modern belt systems is not fully clear. Lower neck metrics may be a determinant of the efficacy of these systems. However, recording and analyses of lower neck load cell data in frontal impacts have been limited in the literature. This paucity has contributed to inadequate understanding of the interrelationships between head-neck kinematics and neck loads. This was an impetus for the current study.

This study offers generic restraint-based data and addresses biofidelity differences between dummies, and dummies of the same family with differing anthropometry. These data are critical for off-center and small overlap frontal crashes where airbag efficacy is often not the most optimum. In addition, this study is particularly applicable for adult rear seat occupants to whom the primary protection is from the three-point belt system. Research focusing on rear seat occupant safety is beginning to appear in literature and this study adds to the current knowledge.

Repeated tests showed consistency. Head and neck kinematics were different between the two mid-size dummies, with the Thor dummy showing greater excursions in the sagittal plane than the Hybrid III dummy. A comparison of data with PMHS tests from our laboratory indicated that the former dummy is closer to the biological specimen. An initial analysis of these data indicate that the intercept values for lower neck bending moments are 100 Nm for the Thor and 200 Nm for the Hybrid III mid-size male dummies. Forces are a direct consequence of head kinematics while moments are more complex, especially at the lower neck. Acknowledging that the 1970s-designed Hybrid III dummy is based on few PMHS and human volunteer responses, and the more recent Thor dummy used additional data, it is reasonable to expect a greater sensitivity for the latter device. The design and construction of the neck are different between the two dummies. Chest compliance through a modified and more physiologic ribcage design in the Thor dummy may be a factor.

CONCLUSIONS
Peak lower neck forces and moments showed greater sensitivity than upper neck loads. Peak upper neck moments were more sensitive than peak upper neck forces. The pattern was consistent for lower neck loads. At the upper neck, moments in the Thor dummy were more sensitive than the moments in the mid-size Hybrid III male dummy; moments were least sensitive in the large-size dummy; and forces were not as distinct across all dummies and changes in velocities. At the lower neck, moments were more sensitive in the Thor dummy than both Hybrid III dummies, and this was true for all change in velocities; moments in the mid-size Hybrid III dummy were only distinctive from the large-size dummy at the highest change in velocity. The Thor dummy appears to be better suited for assessing injury potential in frontal impacts and this conclusion is applicable specifically to the off-center vector or to rear seat occupants.

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