

Jaw Loading Response of Current ATDs

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ABSTRACT

Biomechanical surrogates are used in various forms to study head impact response in automotive applications and for assessing helmet performance. Surrogate headforms include those from the National Operating Committee on Standards for Athletic Equipment (NOCSAE) and the many variants of the Hybrid III. However, the response of these surrogates to loading at the chin and how that response may affect the loads transferred from the jaw to the rest of the head are unknown. To address part of that question, the current study compares the chin impact response performance of select human surrogates to that of the cadaver.

A selection of Hybrid III and NOCSAE based surrogates with fixed and articulating jaws were tested under drop mass impact conditions that were used to describe post mortem human subject (PMHS) response to impacts at the chin (Craig et al., 2008). Results were compared to the PMHS response with cumulative variance technique (Rhule et al., 2002). A Hybrid III based surrogate headform with an articulating jaw demonstrated the best overall performance of the surrogates evaluated.

INTRODUCTION

Head injuries resulting from motor vehicle crashes remain a significant public health issue in the United States. The Centers for Disease Control and Prevention (CDC) estimate that 50,000 people die each year in the United States due to traumatic brain injury (TBI) and that 20% of TBI injuries result from motor vehicle crashes. Eigen and Martin (2005), in studying National Automotive Sampling System – Crashworthiness Data System (NASS-CDS) frontal crashes from 1997 to 2003,

found that \$6 billion of societal cost resulted from head injuries and that fatalities attributed to head injuries were second only to those sourced to the thorax.

The Insurance Institute for Highway Safety (IIHS) and the National Highway Traffic Safety Administration (NHTSA) both evaluate the effectiveness of restraint systems and other interior components in the prevention of head injuries. Among other things, the NHTSA regulates the compliance of upper interior and instrument panel components in Federal Motor Vehicle Safety Standard (FMVSS) No. 201 (NHTSA, 2007). The test protocol for the upper interior portion of FMVSS No. 201 involves the projection of a Hybrid III 50th percentile male based headform at 12 or 15 mph into prescribed locations on the upper interior of the vehicle. The test protocol for many of the targeted locations can result in chin contact that contributes to the measured acceleration at the headform's center of gravity (CG). The IIHS evaluates the effectiveness of restraint systems in their frontal offset deformable barrier (ODB) full-scale crash test protocol (IIHS, 2008). They found that 52% of seat belt load limiter equipped vehicles tested as of June 2006 in the frontal ODB protocol resulted in head contact through the airbag to the steering wheel with two-thirds of those strike-throughs resulting in the peak measured resultant head acceleration for the respective tests (Brumbelow et al., 2007). Whether it is in component or full-scale evaluations by the NHSTA or the IIHS or real world crash conditions, head contacts involving the potential for facial or chin loading do occur.

In addition to automotive related testing, anthropometric test device (ATD) headforms are currently used for the evaluation and certification of football helmets. The Hybrid III and National Operating Committee on

Standards of Athletic Equipment (NOCSAE) surrogate headforms are commonly used in those tests. Newman and Gallup (1984), Melvin and Shee (1989), Perl et al. (1989), and Melvin et al. (1995) have studied biofidelity improvements to the Hybrid III headform with emphasis on facial loading response. However, there currently is no commercially available surrogate that was validated using chin impact response data. Additionally, there is no commercially available surrogate with an articulating jaw that can be used in the evaluation of mouthguards.

Few have evaluated the response of the Hybrid III and other surrogates to loading of the jaw. Ward (1985) completed drops to the lateral parietal area and midsagittal forehead and mandible of the Part 572 and Hybrid III 50th male headforms and compared those to drop tests of four post mortem human subjects (PMHS). Impacts were oriented such that the direction of force was through the head CG. Resultant accelerations were lowest in the mandible impacts, which lead the author to conclude that jaw motion relative to the skull dissipated energy. The nature of the jaw motion was not described in the paper. The average forces seen by the cadavers were about half that seen in the surrogate headform impacts in the drop tests to the jaw. Newman and Gallup (1984) completed drops similar to those completed by Ward (1985) with a modified Hybrid III headform with a compliant, but non-articulating mandible and showed a four to five fold decrease in head acceleration versus an unmodified Hybrid III headform, but noted that they felt the response was too soft.

The primary aim of this study was to compare the chin impact response of a selection of ATD headforms against that of PMHS. Many have developed biomechanical response corridors that can be used as biofidelity requirements finite element models and/or ATDs (Kroell et al., 1971; Hardy et al., 2001; Stemper et al., 2001; Maltese et al., 2002; Bir et al., 2004; Wheeldon et al., 2006; Craig et al., 2008). The current study uses the PMHS chin impact response corridors and data documented by Craig et al. (2008) to evaluate and compare the response of current ATD headforms. Hybrid III and NOCSAE based surrogates with fixed and articulating jaws were evaluated in this study. The comparisons to PMHS data and between surrogates was done through comparisons of peak response data and through the use of a biofidelity ranking method.

BACKGROUND: SURROGATE HEADFORMS - The NOCSAE headform was developed by Hodgson (1973) as an anthropometrically correct headform that could be used in the testing of helmets. It comes in three sizes: small male, midsize male and large male. The NOCSAE headform, unlike the Hybrid III, is primarily used for sports equipment and has not been adapted for automotive applications. Until recently the headform only accommodated a rigid neck and was used primarily for helmet certification. Unlike the Hybrid III 50th percentile male surrogate, the NOCSAE surrogate chin

is not backed by a rigid skull and thus is potentially susceptible to greater deformation under chin loading.

The development of a NOCSAE based biomechanical surrogate to determine the protective performance of mouthguards was completed as part of previous unpublished studies done at Wayne State University (Detroit, Michigan). Modifications were made to a small male NOCSAE headform. An articulating jaw was added to simulate the interaction between the temporomandibular joint (TMJ) complex and the base of the skull (Figure 1). The jaw or mandible was made from cast aluminum with accommodations for dental model teeth (Columbia Dentoform Corp., Long Island City, NY). The maxillary arch was also made from aluminum with sockets for teeth. The maxillary arch was mounted to a triaxial load cell that mounted to the base of the skull. Individual x- and z- direction load cells were placed posteriorly and superiorly to the condyles in both TMJ locations. By design, the condyle-load cell interface is metal on metal with no compliant elements. However, the interface between the load cell bracket and the skull of the NOCSAE headform provides a nominal level of compliance. In the current study, the surrogate was also evaluated with 3- and 6-mm thick, 25A hardness thermoplastic polyurethane (TPU) pads that were placed between the condyles and load cells to increase the compliance of the mandible/TMJ.

The Hybrid III 50th percentile headform (ATD 502) was developed in 1973 by General Motors under contract from the NHTSA (Foster et al., 1977). The basis for the ATD 502 headform was described by Hubbard and McLeod (1973), Hubbard and McLeod (1974) and Hubbard (1975). Studies looking at potential refinements to the Hybrid III headform have included the incorporation of a load sensing face, a frangible face, a compliant jaw, and an articulating jaw. Melvin and Shee (1989) used the rigid bar impact response data of Nyquist et al. (1986) as biofidelity requirements for the development of a Hybrid III headform with a frangible face. The final production version of that headform was described by Melvin et al. (1995). Other studies documented Hybrid III headform modifications to the face and jaw that were not introduced into production. These included a deformable face for the Hybrid III with load sensing capabilities developed by Perl et al. (1989) and a compliant mandible developed by Newman and Gallup (1984.)

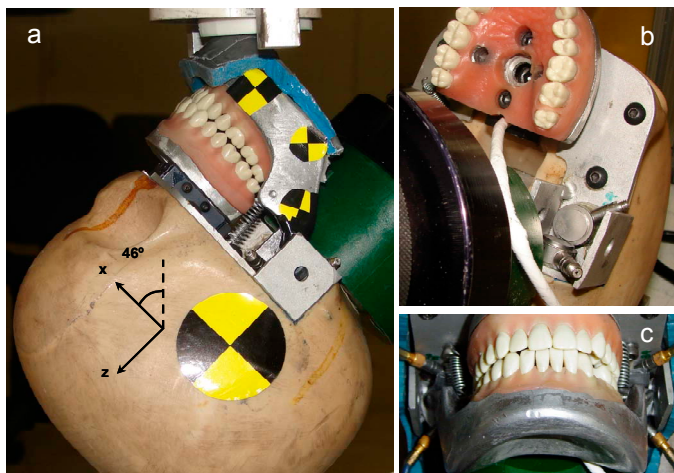


Figure 1. NOCSAE articulating jaw surrogate (without skin): a) Lateral view as tested, b) Inferior view showing upper dentition and TMJ load cells, c) Frontal view.

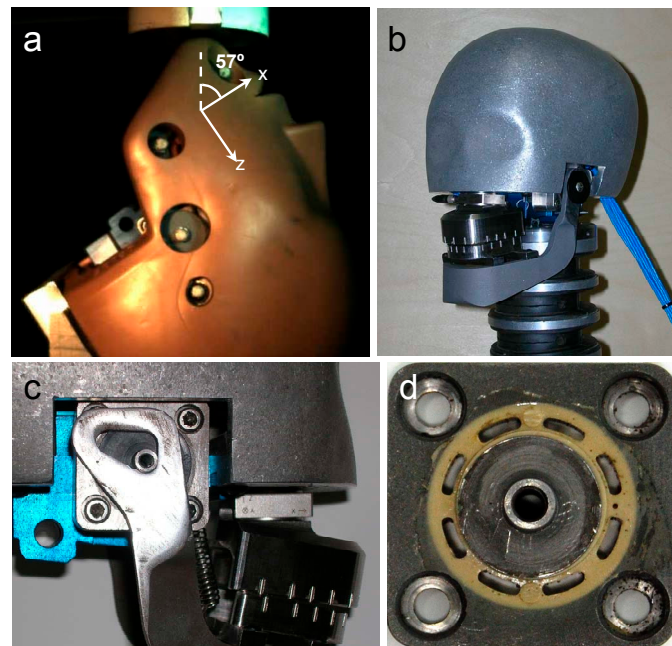


Figure 2. Hybrid III articulating jaw surrogate: (a) Lateral view as tested with skin, (b) Without skin, (c) TMJ close-up, (d) Slotted condylar disc. (b), (c) and (d) courtesy of Biokinetics and Associates, Ltd., Copyright 2007.

Figure 2 shows the Hybrid III 50th percentile male surrogate with an articulating jaw developed by Biokinetics and Associates, Ltd. (Ottawa, Canada) using, in part, the PMHS chin impact data from Wayne State University (Craig et al., 2008). The primary aim in developing this surrogate was to provide a device that could be used in the evaluation of mouthguards. The refined Hybrid III headform incorporates a steel mandible with steel dentition. The steel jaw and rigid attachment of the steel dentition to the jaw were not designed as compliant elements. However, the attachment of the jaw to the skull, in the area where the mandibular condyles or TMJ would be, involved the use of cast polyethylene bushings that could be modified in efforts to replicate the response documented in PMHS chin impacts. The bushing or condylar ring (Prothane, Inc.) had slots to allow for a bi-linear response under chin loading in the evaluated design (Figure 2d). A bi-linear response was observed in chin impact testing of PMHS, where stiffness of 475.1 ± 199.8 kN/m was observed for loads up to 0.6 kN and stiffness of 2381.6 ± 495.7 kN/m for loads from 0.6 to 3.25 kN (Craig et al., 2008). The condylar bushings evaluated in the current study had linear shore hardness values of 70A or 95A.

METHODS

BACKGROUND: TEST METHODS - Figure 3 shows the drop mass impact orientations and impact technique developed to study the biomechanics of chin impact (Craig et al., 2008). Craig et al. (2008) aimed to develop a drop mass condition that would replicate the magnitude and duration of loading seen in the re-enactments of facemask impacts in the NFL (Condition A, Pellman et al., 2003). A Hybrid III 50th percentile male headform with a fixed triaxial load cell mounted to the jaw (Robert A. Denton, Inc.; Biokinetics and Associates, Ltd.) was used to develop the PMHS chin impact test methods that were used in the chin impact testing of the current study. A 30° lateral drop mass impact (2.8 kg from 500 mm) to the chin of the Hybrid III surrogate with the plane of loading through the TMJ (Condition #2) best matched NFL Condition A (Craig et al., 2008). The drop mass included an 18-mm thick, closed-cell, 3.8-pcf polyethylene foam pad (Minicel© L380, Sekusui Voltek, LLC) to achieve comparable peak force and loading durations to those in Condition A. In order to provide symmetrical loading of the PMHS mandible, the plane of loading from Condition #2 was retained, but the lateral component was not. The result was Condition #1. Similar impact orientations to Condition #1 were used previously by Hodgson (1967), Nahum et al. (1968) and Schneider and Nahum (1972) in their mandible fracture studies.

Figure 3 shows the test stand that was used in PMHS chin impacts (Craig et al., 2008). The test stand had an aluminum frame supporting a tube for guiding a drop

mass and an aluminum reaction surface. This same test stand was used to complete drop mass impacts to the chins of surrogate headforms in the current study.

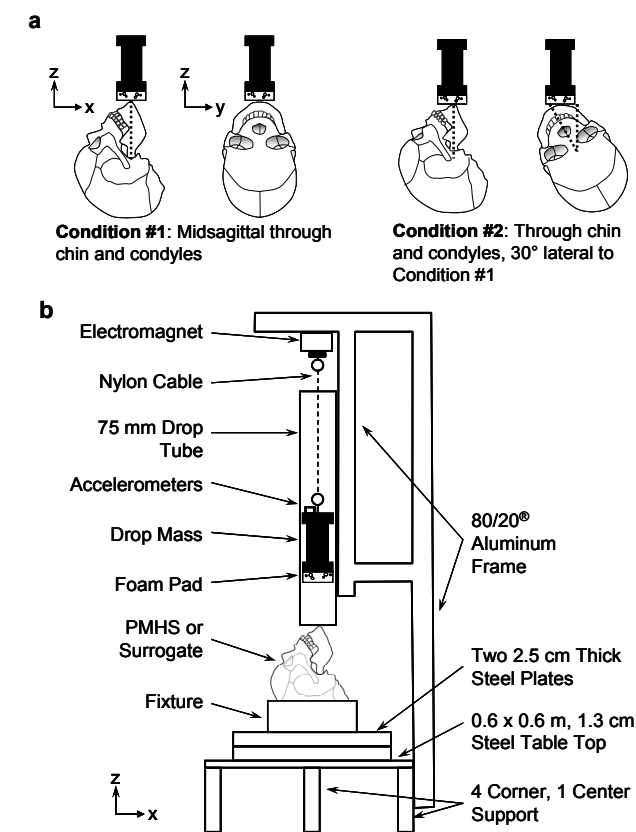


Figure 3. (a) Impact conditions, (b) Test stand.

SURROGATE EVALUATIONS - The aim of this study was to document the response of select surrogate headforms under the drop mass protocol used to produce cadaver chin impact response corridors and to compare the response data to that of the PMHS and between surrogates (Craig et al., 2008). Table 1 lists the surrogates that were tested and the impact conditions that were studied. The primary impact orientation used to document PMHS response (Condition #1) was used in the current study to document surrogate response to chin loading. Each surrogate was impacted a minimum of three times in the drop height and drop mass combinations shown in Table 1 (except as noted). The NOCSAE articulating jaw surrogates were not tested in the 500-mm/5.2-kg drop condition due to durability concerns and those with the TPU inserts were not tested in the 300-mm/2.8-kg drop condition, because of observations noted in the 400- and 500-mm/2.8 kg impacts on those surrogates. The Hybrid III frangible face tests were limited to the 500-mm/2.8-kg condition due to observations made in that condition.

Table 1. Surrogate test matrix

Surrogate	Impact Condition			
	300 mm 2.8 kg	400 mm 2.8 kg	500 mm 2.8 kg	500 mm 5.2 kg
Hybrid III - Base	x	x	x	x
Hybrid III - Frangible Face			x	
Hybrid III - Art Jaw, 70A	x	x	x	x
Hybrid III - Art Jaw, 95A	x	x	x	x
NOCSAE - Mid Male Base	x	x	x	x
NOCSAE - Art Jaw Base	x	x	x	
NOCSAE - Art Jaw, 3 mm TPU ¹		x	x	
NOCSAE - Art Jaw, 6 mm TPU ¹		x	x	

Note(s):

1. NOCSAE surrogates with 3- and 6-mm TPU pads were tested two times each in the 400- and 500-mm, 2.8-kg drop conditions

Three Hybrid III and two NOCSAE based headforms were evaluated in this study. The articulating jaw surrogates were each evaluated with more than one version of energy absorbing material between the condyle area of the mandible and the skull for a total of eight unique surrogate configurations (Table 1). All surrogates were representative of the 50th percentile (Hybrid III) or midsize (NOCSAE) male with the exception of the NOCSAE headform with the articulating jaw that was based on a NOCSAE small male headform. The surrogates represent the current state of the art for headforms used in football helmet and automotive testing of 50th percentile male adult ATDs.

Testing involved drop mass impacts to the chin of the surrogates per previously described cadaveric test methods (Craig et al., 2008). Two drop masses (2.8 and 5.2 kg) with a 20.3-cm² circular, foam covered impact surface were dropped onto the chin of the surrogates. The drop heights were 300, 400 and 500 mm for the 2.8-kg mass and 500 mm for the 5.2 kg. Drop mass acceleration was measured with Endevco™ 7264C-2000 single-axis, translational accelerometers and collected using TDAS PRO™ (DTS, Inc.) at 10,000 Hz. Force was calculated as the product of drop mass acceleration and mass. Acceleration data was filtered using a 1650-Hz Butterworth filter (SAE CFC 1000). Video was recorded by a Redlake MotionXtra HG-100K camera at 2 kHz. The recorded image resolution was 2.55 pixels/mm. Target tracking was done with ImageExpress Motion Analysis/Motion Tracker software (Sensors Applications, Inc.). The accuracy of the tracking software based on assessments made in the current study was 0.045±0.01 mm. Similar to the bi-planar x-ray tracking methods used in the PMHS testing (Craig et al., 2008), the chin displacement measured on the surrogates was limited to photographic points on the jaw and skull and was relative to a fixed reference on the skull. Displacement of the drop mass and compression of the respective urethane or vinyl covering of the surrogate chin was not measured. Chin displacement was corrected to eliminate displacement due to jaw rotation (See Appendix for details).