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# Jaw Loading Response of the Human Relative to Current ATDs

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## ABSTRACT

*Biomechanical surrogate headforms are used in various designs to study head impact response in automotive applications and to develop and/or certify, among other things, American football helmets. The Hybrid III and National Operating Committee on Standards for Athletic Equipment (NOCSAE) headforms have both been commonly used to evaluate the effectiveness of football helmets. However, the response of these surrogates to loading at the chin and how that response affects the loads transferred from the jaw to the rest of the head are unknown. To address part of that concern, the current study compares the chin impact response performance of select human surrogates to that of the cadaver.*

*Surrogates with fixed and articulating jaws were tested under drop mass impact conditions that were used to describe the cadaveric response to impacts at the chin (Craig, 2007). The current study impacted a selection of Hybrid III and NOCSAE headforms with a 2.8 kg drop mass at drop heights of 300, 400 and 500 mm and a 5.2 kg mass at 500 mm. Results were compared to the response corridors. Additionally, the surrogate responses were compared to the mean cadaver response using a cumulative variance technique. A Hybrid III based surrogate headform with an articulating jaw demonstrated the best overall performance of the surrogates evaluated.*

## INTRODUCTION

Force versus time and force versus displacement response corridors have been commonly developed as a requirement for finite element model and/or biomechanical surrogate validation (Kroell et al., 1971; Hardy et al., 2001; Stemper et al., 2001; Maltese et al., 2002; Bir et al., 2004; Wheeldon et al., 2006). Prior research has documented mandible fracture tolerance (Hodgson, 1967; Nahum et al., 1968: Schneider and Nahum, 1972; Nahum, 1975; Huelke and Compton, 1983; Hopper et al., 1994; Unnewehr et al., 2003) and head response under chin impacts (Ward, 1985). Gross deformation of the chin and body of the mandible versus time under chin loading was previously described by Craig (2007).

Others have studied biofidelity improvements to the Hybrid III ATD headform (Newman and Gallup, 1984; Melvin and Shee, 1989; Melvin et al., 1995) with emphasis on facial loading response. The primary aim of this study is to compare the response of a selection of anthropometric test device (ATD) headforms against chin impact response corridors developed from cadaver testing.

Figure 1 shows the force versus time response of the cadaver documented previously by Craig (2007). Coordinates of the upper and lower bound are shown and follow at approximately ±1.5 standard deviations from the mean response. The 5.2 kg, 500 mm force versus time corridor goes to 9 ms, because four of six specimens tested in this condition saw fracture between 9 and 10 ms.

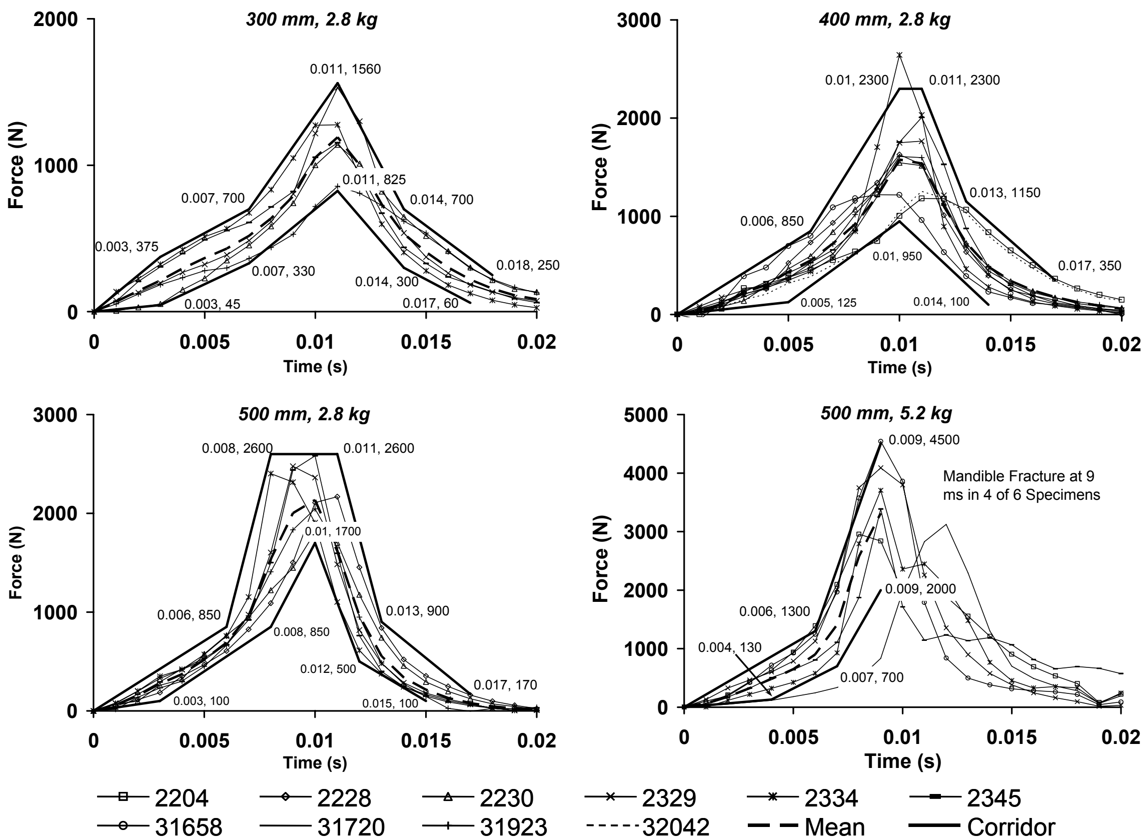


Figure 1: Force vs. time response for cadaver chin impacts (Craig, 2007).

Figure 2 shows force versus chin displacement and average response of the cadaver in each of four drop mass height/mass combinations (Craig, 2007). Peak force ranged from 0.86 to 4.54 kN causing chin displacement of 1.0 to 3.3 mm. The observed force versus displacement response was bi-linear with an average stiffness of 596.3±242.7 kN/m up to 0.6 kN of drop mass load and 3029.9±842.1 kN/m for loading from 0.6 kN to 3.25 kN. The single force versus displacement corridor overlaid on the response data for Condition #1 has left and right bounds with coordinates at 0.6 mm and 1.8 mm at 600 N and 1.1 mm and 3.3 mm at 3250 N, which are at approximately ±1.5 standard deviations from the mean response from twenty-six (26) Condition #1 tests. The data and corridor represent the response of the mandible up to peak drop mass load.

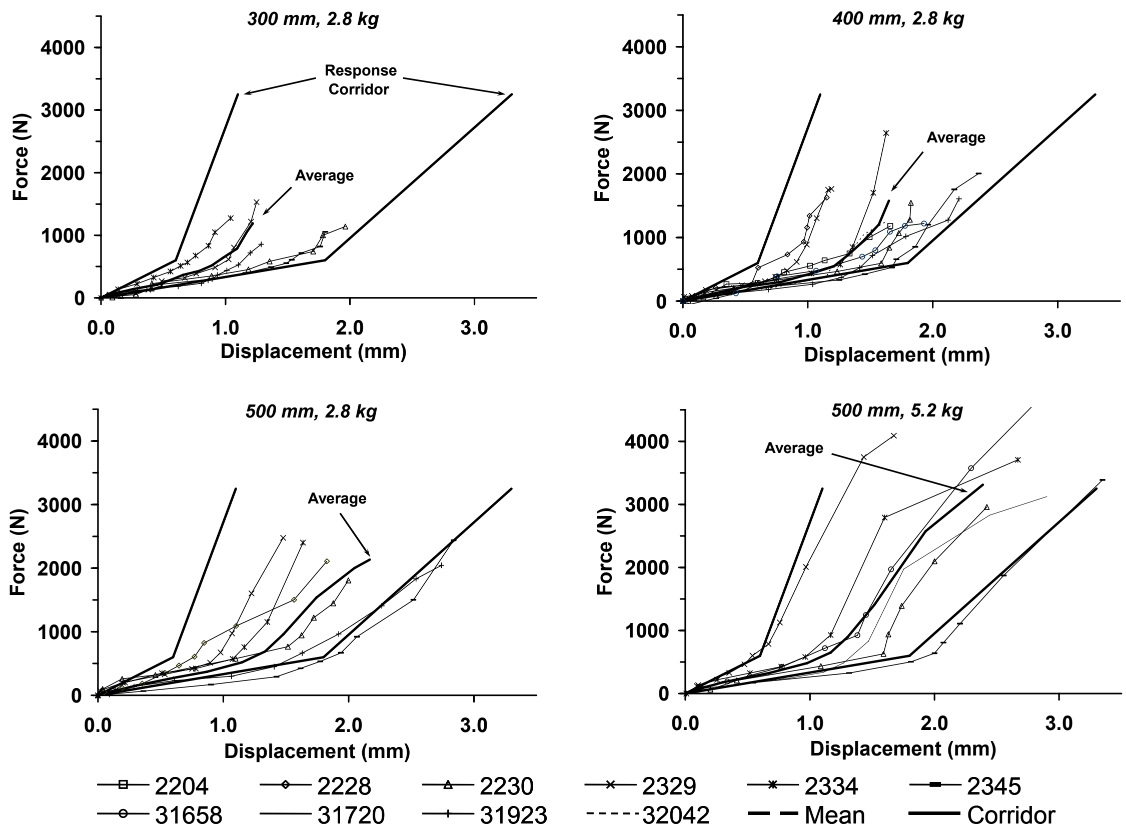


Figure 2: Force vs. chin displacement for cadaver chin impacts (Craig, 2007).

## Background – Surrogate Headforms

ATDs or test dummies are commonly used in the testing of automobiles. The surrogate headform is also currently used for, among other things, the evaluation and certification of the football helmets. The Hybrid III and National Operating Committee on Standards of Athletic Equipment (NOCSAE) surrogate headforms are commonly used in evaluation of football helmets. However, there currently is no production surrogate that was validated, at least in part, using response data from impacts to the chin. The following paragraphs provide a brief summary of the history behind the Hybrid III and NOCSAE headforms that were evaluated in the current study.

### NOCSAE Headforms

The NOCSAE headform was developed by Hodgson (1973) as an anthropometrically correct headform that could be used in the testing of helmets. 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 certification of helmets. Unlike the Hybrid III 50$^{th}$ percentile male surrogate headform, the NOCSAE headform's 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. Modifications were made to a small male NOCSAE headform. An articulated jaw was added to simulate the interaction between the TMJ complex and the base of the skull. The jaw was made from cast aluminum with accommodations for the mounting of dental model teeth (Columbia Dentoform Corp., Long Island City, NY). The maxillary arch was also cast aluminum with sockets for teeth and was attached 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 mandibular condyles in both TMJ locations. By design, the condyle-load cell interface is metal on metal with no compliant elements. In the current study, the surrogate was also evaluated with 3 and 6 mm thick, 25A hardness thermoplastic polyurethane (TPU) pads placed between the condyle and load cells to increase the compliance of the mandible/TMJ.

### Hybrid III 50$^{th}$ Percentile Male Headforms

The Hybrid III 50$^{th}$ percentile headform (ATD 502) was developed in 1973 by General Motors under contract from the National Highway Traffic Safety Administration (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). This headform has been commonly used for the evaluation of football helmets (Pellman et al., 2003a,b; Pellman et al., 2006; Viano et al., 2006; Craig, 2007) and is part of the Hybrid III 50$^{th}$ percentile male ATD used in the NHTSA's New Car Assessment Program (NCAP) and Federal Motor Vehicle Safety Standard (FMVSS) No. 208.

Refinements to the Hybrid III headform have included the incorporation of a load sensing face and articulating jaw. Melvin and Shee (1989) used the response data of rigid bar impact testing of Nyquist et al. (1986) as their performance requirements in developing a Hybrid III headform with a frangible face. The final production version of that headform was described by Melvin et al. (1995).

An articulating jaw was developed for the Hybrid III headform by Biokinetics and Associates, Ltd. (Ottawa, Canada) with involvement from Wayne State University. The refined Hybrid III headform incorporates a steel mandible with metal dentition. The steel jaw and solid attachment of the steel dentition were not designed as compliant elements to match the compression of the mandible observed in cadaver testing. Instead, the attachment of the jaw to the skull, in the area where the mandibular condyles would be, was designed with a tuning feature for matching the chin impact force versus time and force versus chin displacement corridors. In its current design, as evaluated in this study, the jaw was attached through a polyethylene bushing (Prothane, Inc.) or condylar ring that has slots to allow for a bi-linear response under loading of the bushing. The durometers of these rings evaluated in the current study had shore hardness values of 70A and 95A.

## METHODS

### Background: Response Corridor Development

Figure 3a shows the drop mass impact orientations and impact technique developed to study the biomechanics of chin impact (Craig, 2007). A Hybrid III 50$^{th}$ percentile male headform with a fixed triaxial load cell mounted to the jaw (Robert A. Denton, Inc.; Biokinetics and Associates, Ltd.) was used to validate the test methods. A single drop mass condition was established that replicated the magnitude and duration of loading seen in the re-enactments of NFL Condition A (Pellman et al., 2003a). The head orientation, drop mass weight and drop height that best matched Condition A was a 30º lateral impact to the chin with the plane of loading through the TMJ (Condition #2), 2.8 kg and 500 mm, respectively. An 18 mm thick, closed-cell, 3.8 pcf polyethylene foam pad was added to the end of the drop mass to achieve comparable peak force and loading durations to those in Condition A.

Figure 3b shows the test stand previously used by Walilko (2004) and refined for use in the development of cadaver chin impact response (Craig, 2007). 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 in the evaluation of surrogate chin impact response in the current study.

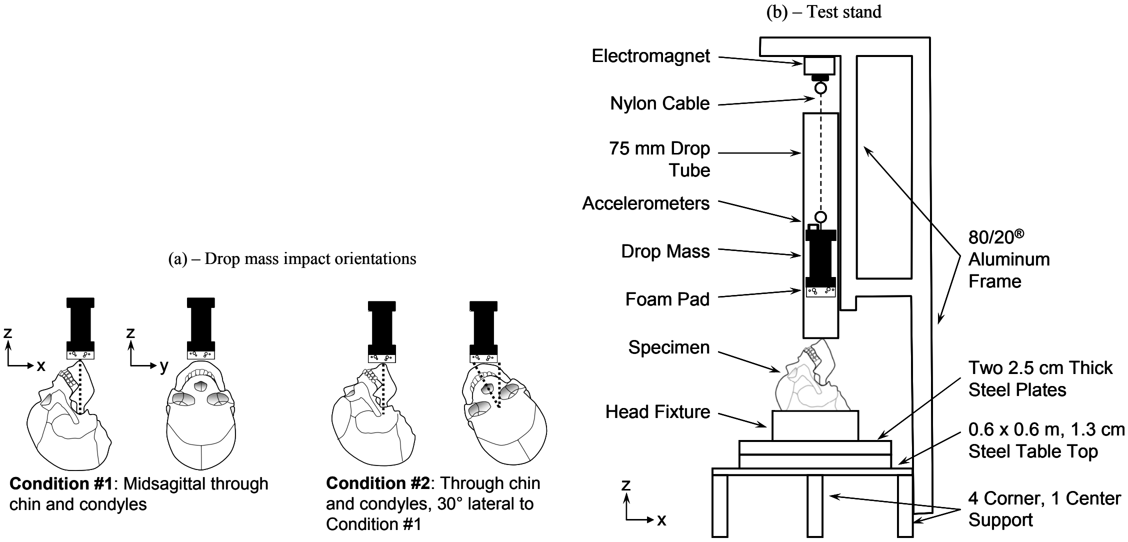


Figure 3: Drop mass impact orientations and test stand.

Though Condition #2 matched the peak responses and duration of NFL Condition A, Condition #1 was the primary impact condition used to develop the cadaver response corridors to chin impact loading (Craig, 2007). Condition #1 involved a mid-sagittal impact to the chin with symmetric, stable loading directed through the condyles that minimizes mandible rotation and load transfer into the upper dentition and maxillae. Similar observations and methods regarding impact orientation with the primary direction of force (PDOF) aimed from the chin through the axis of the condyles were made by Hodgson (1967), Nahum et al. (1968) and Schneider and Nahum (1972) in their mandible fracture studies.

## 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 (Craig, 2007). Table 1 lists the surrogates that were tested and the impact conditions that were studied. Condition #1 was used as the primary tool for documenting and comparing the response of the surrogates versus the force versus chin deflection and force versus time response document in PMHS testing. Each surrogate was impacted a minimum of three times in the impact conditions shown in Table 1.

Table 1. Surrogate test matrix.

| | Impact Condition | | | |
|---|---|---|---|---|
| **Surrogate** | 300 mm/2.8 kg | 400 mm/2.8 kg | 500 mm/2.8 kg | 500 mm/5.2 kg |
| Hybrid III - 50th | x | x | x | x |
| Hybrid III Frangible Face - 50th | | | x | |
| Hybrid III Articulating Jaw - 50th, 95A Condyle | x | x | x | x |
| Hybrid III Articulating Jaw - 50th, 70A Condyle | x | x | x | x |
| NOCSAE - Midsize Male | x | x | x | x |
| NOCSAE - Art Jaw Base | x | x | x | |
| NOCSAE - Art Jaw 3 mm TPU Disc | | x | x | |
| NOCSAE - Art Jaw 6 mm TPU Disc | | x | x | |

Force versus time and force versus displacement are compared to the cadaver response corridors (Craig, 2007). Surrogates with fixed jaws were only evaluated for force versus time. Results for force versus deflection were only evaluated for surrogates with articulating jaws. Five different surrogates were evaluated in this study. All were representative of the 50$^{th}$ percentile (Hybrid III) or midsized (NOCSAE) male with the exception of the NOCSAE headform with the articulating jaw which is based on a NOCSAE small male headform. The two surrogates with articulating jaws were tested with different sets of content at the condyles giving a total of eight surrogate combinations tested (Table 1). The surrogates represent the current state of the art for headforms used in football helmet and automotive testing of 50$^{th}$ percentile male adult ATDs.

Testing involved Condition #1 drop mass impacts to the chin of the surrogate per previously described cadaveric test methods (Craig, 2007). Two drop masses (2.8 and 5.2 kg) with a 20.3 $cm^2$ circular impact surface (radius = 2.54 cm) 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. Four accelerometers were mounted to the top of the drop mass with one each measuring acceleration in the x-, y- and z-directions. A redundant z-direction accelerometer was also included. Drop mass force was calculated as the product of drop mass weight and z-direction acceleration. 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. Target tracking was done with ImageExpress Motion Analysis/Motion Tracker software (Sensors Applications, Inc.).

The Condition #1 impact orientation for the surrogates was determined based on the projected location of the plane between the condyles and chin of the given surrogate. By design, the Hybrid III articulating jaw headform is tested at 57º from the transverse or horizontal plane. The cadavers used to develop the chin impact response corridors averaged 49.6±6.1º (Craig, 2007). The NOCSAE articulating jaw headform was set up at 46º to get the plane of impact through the condyles. The respective base and frangible face Hybrid III and base NOCSAE surrogates were tested with same set-up as their articulating jaw versions.

The force versus time and force versus displacement results were overlaid on the cadaver corridors for Condition #1 impacts to the chin. The assessment of biomechanical biofidelity was based on comparison to the response corridors and to mean cadaver response using cumulative variances as described by Rhule et al. (2002). The evaluation of cumulative variances was limited to the external biofidelity measured as the force versus time of the drop mass and displacement versus time for the chin.

## Comparing Surrogate and Cadaver Response

Biofidelity requirements and determinants for measuring the degree of biofidelity are necessary to assess the performance of a human surrogate against human biomechanical response. Historically, peak acceleration, force versus time, displacement versus time, and force versus displacement targets based on human response have been used. Rhule et al. (2002) discussed measures for comparing the internal and external biofidelity of surrogates. They proposed a biofidelity ranking measure represented by the ratio of dummy cumulative variance and cadaver cumulative variance. Dummy Cumulative Variance (DCV) is defined by

$$DCV = \sum_{t=0}^{n} DV(t)^2$$

where *DV(t)* is the cumulative difference between the mean dummy response and the mean cadaver response. Cadaver Cumulative Variance (CCV) is defined as

$$CCV = \sum_{t=0}^{n} CV(t)^2$$

where *CV(t)* is the cumulative variance or cumulative difference between the mean cadaver response and the mean plus one standard deviation cadaver response. Figure 4 shows an example of these measures for the 400 mm/2.8 kg force versus time curves and the surrogate response of the 95A Hybrid III with articulating jaw. The square root of the ratio of these values (DCV divided by CCV) was termed the Response Comparison Value (RCV). The lower the RCV, the better the surrogate matches the response of the human. A surrogate headform should target a mean chin impact response that matches as closely as possible to the mean response of the cadaver to achieve biomechanical fidelity.

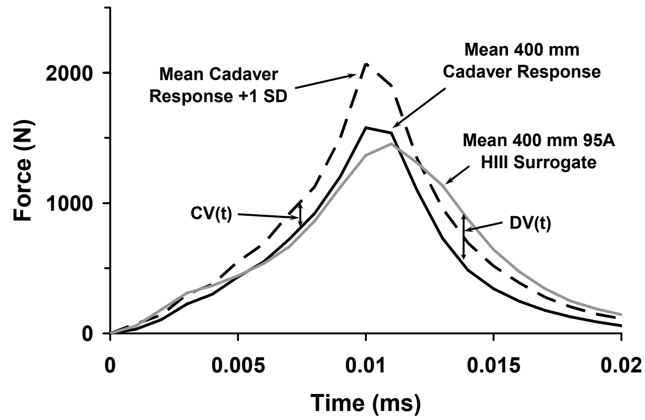


Figure 4: Dummy and cadaver cumulative variance.

# RESULTS

A total of 172 Condition #1 chin impact tests of surrogates were completed. Table 2 shows the average peak force and displacement for the four Condition #1 impacts of eight surrogates versus the mean results from cadaver testing. The coefficient of variation target of 5% proposed by Tennant et al. (1974) was exceeded in a majority of conditions. However, with only a few exceptions was it higher than 10%.

Table 2. Condition #1 – surrogate vs. cadaver peak force and displacement.

| | | Cadaver | | Hybrid III - Base | | Hybrid III - Frangible Face | | Hybrid III - 95A Art Jaw | | Hybrid III - 70A Art Jaw | | NOCSAE Mid Male Base | | NOCSAE Art Jaw Base | | NOCSAE Art Jaw - 3 mm TPU | | NOCSAE Art Jaw - 6 mm TPU | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Condition | Measure | Avg | Std Dev | Avg | Std Dev | Avg | Std Dev | Avg | Std Dev | Avg | Std Dev | Avg | Std Dev | Avg | Std Dev | Avg | Std Dev | Avg | Std Dev |
| 300 mm 2.8 kg | Force (N) | 1191 | 244 | 1141 | 115 | NT | | 1002 | 52 | 899 | 62 | 978 | 48 | 1062 | 67 | NT | | NT | |
| | Chin Disp (mm) | 1.47 | 0.39 | NA | | | | 0.42 | 0.02 | 0.77 | 0.08 | NA | | 0.33 | 0.01 | | | | |
| 400 mm 2.8 kg | Force (N) | 1651 | 461 | 2057 | 203 | NT | | 1318 | 112 | 1303 | 37 | 1247 | 56 | 1384 | 21 | 1253 | 97 | 1184 | 54 |
| | Chin Disp (mm) | 1.81 | 0.44 | NA | | | | 0.53 | 0.01 | 0.94 | 0.11 | NA | | 0.47 | 0.06 | 2.59 | 0.31 | 4.55 | 0.01 |
| 500 mm 2.8 kg | Force (N) | 2247 | 293 | 2774 | 220 | 895 | 45 | 1830 | 68 | 1643 | 51 | 1507 | 53 | 1658 | 116 | 1632 | 10 | 1367 | 29 |
| | Chin Disp (mm) | 2.19 | 0.53 | NA | | NA | | 0.77 | 0.09 | 1.05 | 0.06 | NA | | 0.46 | 0.12 | 2.50 | 0.07 | 4.76 | 0.10 |
| 500 mm 5.2 kg | Force (N) | 3635 | 603 | 5504 | 155 | NT | | 3742 | 331 | 3568 | 231 | 2742 | 77 | NT | | NT | | NT | |
| | Chin Disp (mm) | 2.60 | 0.60 | NA | | | | 1.38 | 0.14 | 1.75 | 0.05 | NA | | | | | | | |

Independent t-tests comparing the mean surrogate and cadaver values were completed on base production headforms. The base Hybrid III 50th showed significantly higher force in the 400 mm/2.8 kg ($t=2.275$, $p=0.022$), 500 mm/2.8 kg ($t=3.558$, $p=0.003$) and 500 mm/5.2 kg ($t=7.142$, $p<0.001$). Impact force was not significantly different at 300 mm/2.8 kg ($t=-0.401$, $p=0.351$). The effect of the foam on the drop mass and the skin of the surrogate tend to equalize the response in the 300 mm/2.8 kg condition. The stiffness of the base Hybrid III jaw becomes more apparent and more significantly different than the human response with increase impact energy. The midsize male NOCSAE headform showed significantly lower average peak force compared to cadavers at 400 mm/2.8 kg ($t=-2.99$, $p=0.015$), 500 mm/2.8 kg ($t=-6.096$, $p<0.001$) and 500 mm/5.2 kg ($t=-3.571$, $p=0.007$). The chin of the NOCSAE headform appeared to be much more compliant than the Hybrid III and cadaver. The Hybrid III was designed with 7.6 mm of vinyl skin covering the chin to simulate that of the human. However, the urethane foam of the NOCSAE chin is not backed by solid skull and as a result has a significantly lower observed stiffness than the Hybrid III or human chin.

A comparison of mean response of the articulating jaw surrogates versus cadavers was also completed. The NOCSAE articulating jaw surrogate with 3 mm of TPU in the condylar area was the closest of the three NOCSAE articulating jaw headforms to meeting the cadaver response corridors in testing at 400 and 500 mm drop heights with the 2.8 kg mass (Figure 5). However, the forces measured were significantly lower at both 400 mm ($t=-2.36$, $p=0.022$) and 500 mm ($t=-5.138$, $p=0.002$) as was chin displacement at 400 mm ($t=3.221$, $p=0.046$). Chin displacement was not found to be significantly different at 500 mm ($t=1.425$, $p=0.105$).

The Hybrid III based articulating jaw surrogates with 70A and 95A condylar bushings both had peak displacements that were significantly less than the cadaver in every drop condition. Force was also lower, except for the 500 mm/5.2 kg impacts with the 95A bushing. Significant differences in average peak force were found at 400 mm/2.8 kg for the 70A ($t=-2.242$, $p=0.027$) and 95A ($t=-2.545$, $p=0.027$) bushing equipped surrogates and again at 500 mm/2.8 kg with both the 70A ($t=-3.315$, $p=0.008$) and 95A ($t=-5.186$, $p=0.002$) condylar bushings. The 70A condylar bushing surrogate also showed significantly lower average peak force compared to the cadaver for the 300 mm/2.8 kg drop condition ($t=-2.545$, $p=0.027$). However, the average force versus time response of the 95A Hybrid III surrogate did stay completely within the cadaver response corridor (Figure 5).

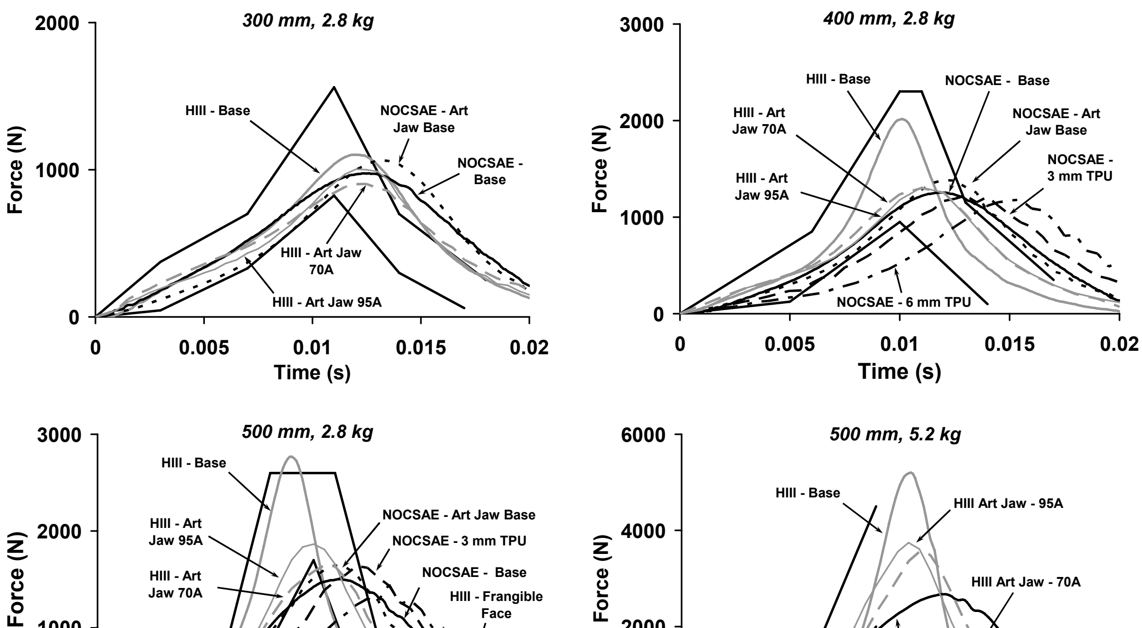


Figure 5: Force vs. time for Condition #1 impacts to Hybrid III and NOCSAE headforms.

In addition to comparing mean surrogate responses to those from cadaver testing, the force versus time response of surrogates tested was evaluated against the cadaver response corridors (Figure 5). The surrogates tested at 300 mm/2.8 kg generally stayed within the corridor, with the exception of the NOCSAE surrogates. The Hybrid III surrogates all performed within the corridor at 400 mm/2.8 kg. However, the NOCSAE surrogates all resulted in longer duration loads as seen in the 300 mm tests. The 6 mm TPU NOCSAE articulating jaw surrogate is especially soft in response early, indicating along with the peak displacement value shown in Table 2 that a 6 mm TPU disc is too thick and/or too soft. The 500 mm/2.8 kg condition again shows the Hybrid III headforms coming close to or staying within the corridor. The Hybrid

III frangible face surrogate had significantly lower force ($p<0.001$) compared to the cadaver response. While the stiff foam insert did crush in these tests, it appears that design was not made to perform under angled impacts of the chin relative to the transverse plane, but instead under impacts parallel to the transverse plane (perpendicular to the face and insert).

Only the NOCSAE and Hybrid III base and Hybrid III articulating jaw surrogates were tested at 500 mm with the 5.2 kg mass. The NOCSAE articulating jaw headform was excluded due to durability concerns given the higher loads typically seen in that condition. The corridor for this drop mass/height only went out to 9 ms given fractures seen in four of six cadavers tested in this condition. As such, it was easier for surrogates to successfully stay within its bounds.

The force versus chin displacement response was evaluated in the NOCSAE and Hybrid III based headforms with articulating jaws. The NOCSAE based headform proved too stiff as compared to the human response corridor (Figure 6). Its displacement was significantly less in the 400 mm/2.8 kg and 500 mm/2.8 kg conditions than the cadaver response ($p<0.001$). The addition of the TPU material superior and posterior to the condyle between the condyle and the x- and z-direction load cells did produce a more compliant response. However, no further tuning was pursued on this headform.

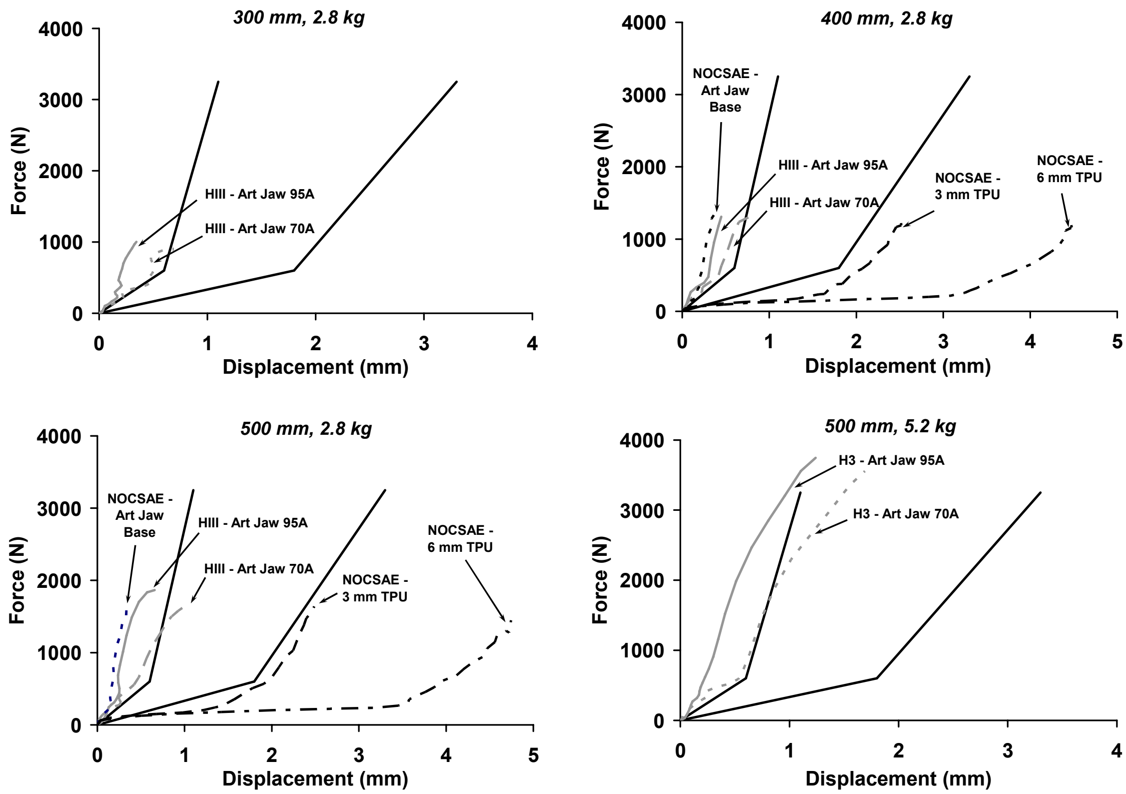


Figure 6: Force vs. chin displacement for Condition #1 impacts to Hybrid III and NOCSAE headforms.

The tests of the Hybrid III based headform with an articulating jaw produced results that followed the "stiffer" border of the human response corridor (Figure 6). This follows the previously stated comparison of means that showed significantly higher forces versus the cadaver. The softer material of the 70A model had significantly more peak chin point displacement than the 95A model in the 300 mm/2.8 kg ($t=-7.514$, $p=0.008$), 400 mm/2.8 kg ($t=-6.344$, $p=0.012$), 500 mm/2.8 kg ($t=-5.023$, $p=0.004$) and 500 mm/5.2 kg ($t=-4.321$, $p=0.016$). Peak drop mass force was only significantly different in the 500 mm/2.8 kg condition ($t=5.989$, $p=0.002$). The 70A model consistently had response which was close to meeting the requirements of the corridors. Seemingly minor modification, a slightly softer early response through use of lower hardness materials, may bring the 70A version within the borders for all drop conditions, without significantly changing peak force. The early part of the event is meant to duplicate the low resistance seen as the condyle displaces rearward and upward towards the mandibular fossa with relatively low resistance.

Response comparisons were made between the surrogates using the previously described methods of comparing cumulative variance of cadaver response versus the variance of mean surrogate versus mean cadaver response. Where appropriate, the Response Comparison Values (RCV) for each of the four drop conditions were averaged for both force and displacement. Table 3 shows the results for the two base non-articulating jaw surrogates and for the Hybrid III articulating jaw surrogates. The base NOCSAE and Hybrid III headforms only show comparison values for force. The base Hybrid III had a lower RCV than the NOCSAE mid-sized male indicating that the Hybrid III headform does a better job of matching human force versus time response. The Hybrid III articulating jaw surrogate with the 95A condyles had the best ratio between surrogate and cadaver cumulative variance related to peak drop mass force (0.83). A value of less than 1.0 indicates that the surrogate variance is less than the cadaver variance (mean + 1 standard deviation) relative to the cadaver mean response. The 70A surrogate had the lower value for chin displacement as compared to 95A (1.40 vs. 1.86). Both Hybrid III based articulating jaw surrogates performed better than the NOCSAE based articulating jaw surrogates when comparing the average of the force and chin displacement Response Comparison Values.

Table 3. Cumulative response comparison for four main surrogates.

| | Surrogate | Measure | Response Comparison Value | Average[1] |
|---|---|---|---|---|
| Base Surrogates | HIII - 50th Male | Force | 1.36 | NA |
| | NOCSAE - Mid Sized Male | Force | 1.75 | NA |
| Articulating Jaw Surrogates | HIII - 50th with 95A slotted condylar ring | Force | 0.83 | 1.35 |
| | | Displacement | 1.86 | |
| | HIII - 50th with 70A slotted condylar ring | Force | 1.18 | 1.29 |
| | | Displacement | 1.40 | |
| | NOCSAE: No TPU Disc[2] | Force | 1.48 | 1.94 |
| | | Displacement | 2.40 | |
| | NOCSAE: 6 mm TPU Disc[2] | Force | 2.93 | 4.21 |
| | | Displacement | 5.50 | |
| | NOCSAE: 3 mm TPU Disc[2] | Force | 2.26 | 1.98 |
| | | Displacement | 1.70 | |

Notes:
1. Given equal weight to force and displacement
2. Only includes 400 and 500 mm, 2.8 kg impacts

## CONCLUSIONS

The response of surrogates was studied through comparison of means, evaluation against response corridors and through comparison of cumulative variances. The surrogate that performed the best overall was the Hybrid III $50^{th}$ with articulating jaw and the shore 70A hardness condylar bushings. Though displacement was significantly lower compared to averaged cadaver response, it was better than seen in the NOCSAE based articulating jaw headform with 3 mm TPU pad when comparing the results at 400 mm/2.8 kg and 500 mm/2.8 kg. Also significant was the finding that the base NOCSAE headform had significantly lower drop mass loads than the Hybrid III based surrogates. The lower Response Comparison Value (RCV) indicates a more biofidelic response for the base Hybrid III as compared to the mid-sized male NOCSAE headform. So, while the Hybrid III is stiffer than the cadaver, the NOCSAE headform is softer, but with even greater variance to mean cadaver response than that of the Hybrid III. Finally, it was concluded that the frangible face Hybrid III is not appropriate for use in testing that involves angled impacts to the jaw.

In conclusion, the Hybrid III surrogate with an articulating jaw developed by Biokinetics and Associates, Ltd. makes significant improvements over the base Hybrid III headform for chin loading. The Hybrid III still acts as a useful tool for gathering comparative responses of sports equipment, especially for impacts involving significant loading through chin given its superior force versus time response in chin impacts compared with the NOCSAE headform, but it does not accommodate the moving jaw necessary to test mouthguards. In its current state, the surrogate with 70A condylar bushings provides force versus time response that is second only to the 95A, but with better displacement versus time response per the methods of Rhule et al. (2002) and is closer to meeting the requirements of the force versus displacement corridor. It has taken into account a number of the anthropometric and response related biofidelity requirements. Though further tuning and updates are likely required, in its current form, the surrogate could be used as an effective tool for researching any potential jaw and head impact response differences in performance that may exist with mouthguard use.

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# DISCUSSION

PAPER: **Jaw Loading Response of the Human Relative to Current ATDs**

PRESENTER: ***Matthew Craig, NHTSA***

**Q**UESTION: *Stephan Duma, Virginia Tech*
Matt, it's a real nice study. One other question is: How are you measuring? With the high-speed x-ray on the cadavers, you're measuring jaw displacement from the targets. In the dummies, what are you calling that displacement, your force displacement?

**A**NSWER: Yes. In the dummy, I didn't go into a lot of detail in that. We assumed the jaw to be pretty much rigid for the Hybrid III. It's hard to see behind here, but we measured point on the chin, point on the mandible, point at the condyle and we'd measure the displacement of this chin target versus a fixed reference on the skull. And that was our displacement equivalent to measuring the chin point displacement in the cadaver.

**Q:** What's the thickness of the skin cover on the Hybrid III jaw there?

**A:** At the jaw, I think it's approximately 8 mm.

**Q:** I'm surprised. If you go to your surrogate response, you get, like, a thousand Newtons at, like a half a millimeter. I'm just really surprised. If you got 8 mm of skin, I'm surprised you can get a thousand Newtons in a half a millimeter. See what I'm saying?

**A:** Right.

**Q:** That's why I was just wondering how you are calling—what you're measuring displacement, because that just seems not what I would think. If you can kind of push on the chin and a half a millimeter.

**A:** The displacement was a little lower than it should have based on what we saw, you know, with the chin and it's not measuring the displacement of the foam or skin. It's measuring the displacement of the bone, was the intent. So everything between the drop mass, the drop mass foam, the actual skin tissue of the specimen or surrogate, you know, those are compliant elements. We were looking more at how the bone is deforming and moving.

**Q:** Okay. Thanks.

**Q:** *Guy Nusholtz, DaimlerChrysler*
Could you go back to the slide where you showed the differences between the dummies in terms of cumulative variance? It was kind of tough to read, but it didn't look like there was a whole lot of difference between the Hybrid III and the one with the articulating jaw. Which numbers are those in?

**A:** Yes. If you look at the Hybrid III base, which is, you know, just a comparison of force. Sorry. It's pretty small.

**Q:** It looks like 1.36.

**A:** That's correct. And then when you're looking at—

**Q:** And then you've got 1.4.

**A:** Yes. That's chin displacement and then force. And then—It's hard to compare just the base surrogate because we weren't—the skull doesn't deform so we're not really measuring deformation of the base surrogate. We're just measuring the force time history. But if you look at the—

**Q:** So if you look at the force—

**A:** But if you look at the force, it's 1.18 so it correlates—or, it does a better job in comparison to the cadaver. And then versus a base surrogate, which doesn't deform at all, it at least allows for deformation.

**Q:** You got 1.4.

**A:** Right.

**Q:** Okay. So, the Hybrid III with the 70-A slotted is 1.18?

**A:** Correct, for force, and then 1.14 for displacement. And giving equal weighting between the two, it's just an average of 1.29.

**Q:** Okay. So, how many tests did you run?

**A:** For each surrogate, there were three tests.

**Q:** Three tests. Okay. How significant do you think these numbers are? It looks like there was a lot of scatter in your data.

**A:** Yes. I mean that's a good question. I didn't do a detailed statistical analysis on it to know if it's significantly different. I know, compared to the cadaver, we saw that the Hybrid III, force-wise, in the base format, was always higher except for the very lowest strap height whereas with the articulating jaw, it was not schematically different than just doing a comparison of means. Similarly with chin displacement, it was always less, but it was on the stiffer side, which is possibly appropriate for the target population anyway.

**Q:** Okay. Thank you.