Adjusting for the Effect of Shoulder Belt Placement on Hybrid III Sternum Deflection

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Abstract Previous research has shown that the location of the shoulder belt on the Hybrid III dummy strongly influences the sternum deflection measurement, which could reduce the real-world relevance of crash tests making use of this metric. The objective of the current study was to quantify and adjust for the effect of belt placement on the sternum deflection measurement across a range of vehicle designs. Pre-test belt locations were measured using photographs of US NCAP full width (n=207) and IIHS moderate overlap (n=131) tests. Linear regression was used to estimate the effect of the vertical position of the belt relative to the sternum potentiometer on the measured deflection while controlling for other factors. Statistically significant effects were found for both tests, with a 1 mm increase in the vertical position of the shoulder belt estimated to reduce the peak sternum deflection by 0.13 mm in the NCAP test (SE = 0.013 mm; $p < 0.001$) and by 0.06 mm in the IIHS test (SE = 0.018 mm, $p = 0.002$). If all tests had belts centered over the sternum potentiometer, the median sternum deflection would be expected to increase 49% (±5%) in the NCAP test and 18% (±6%) in the IIHS test.

Keywords Crashworthiness, Hybrid III, IIHS, NCAP, thoracic injury.

I. INTRODUCTION

Variations in crash test measurements can be caused by vehicle design differences or by inconsistencies in the test parameters and instrumentation. The latter type of variation may reduce the relevance of a test program to real-world crashes unless its effects can be offset or minimised. Sternum deflection measured with the Hybrid III dummy is the single most-used metric for assessing thoracic injury risk in front crash test programs around the world. However, vehicle restraint systems have changed substantially since the dummy was developed. While the single-point sternum deflection measurement may be sufficient for evaluating injury risks from blunt hub impacts [1-2], modern seat belt and airbag designs can create more asymmetric and localised loading patterns on the thorax, with maximum deflection usually occurring along the line of the seat belt [3]. Research is ongoing to determine the degree to which asymmetric loading contributes to injury risk [4-5]. Capturing this risk with Hybrid III would require additional instrumentation, if it is even possible at all with the dummy's rib cage design [6-7]. At a minimum, however, if the Hybrid III sternum potentiometer does not even capture the peak deflection of the central rib cage, any injury prediction ability the dummy does have [8-9] will be reduced. Perhaps just as importantly for comparative crash testing, if the difference between peak-reported sternum deflection and actual maximum dummy rib cage deflection varies from test to test, the utility of the test program itself will be reduced.

Previous research has identified shoulder belt placement as one factor that does strongly influence the maximum sternum deflection of the Hybrid III 50^{th} percentile male. Horsch *et al.* reported a 34% reduction in deflection when placing the shoulder belt against the neck instead of in a position outside the dummy's belt guide [10]. Their sled tests did not include airbags, and the specific vertical difference in belt position on the dummy was not reported. Eggers *et al*. conducted sled tests with a belt and airbag restraint system and found that raising the belt's upper anchorage point by 90 mm, with an approximate 25 mm increase in the shoulder belt height at the centreline of the dummy, resulted in a peak sternum deflection reduction from 28 mm to 24 mm [6]. Others have shown an effect using the Hybrid III 5^{th} percentile female [11-12].

The National Highway Traffic Safety Administration (NHTSA) and the Insurance Institute for Highway Safety (IIHS) conduct front crash tests for consumer information rating programs using the Hybrid III 50^{th} percentile male dummy. NHTSA evaluates crashworthiness using a full width 56 km/h impact into a rigid wall as part of its New

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Car Assessment Program (NCAP). IIHS now has three front crash tests, but the first was the 40% moderate overlap 64 km/h deformable barrier impact. In these tests, belt placement on the dummy is affected by the dummy seating procedure and location of the upper shoulder belt anchorage. For both the NCAP and the IIHS tests, the vehicle manufacturer is permitted to specify the position of the upper anchorage, and typically selects the uppermost location for 50th percentile male dummy. In the NCAP test, the seat is positioned longitudinally in the centre of its adjustment range. IIHS developed an alternative seating procedure based on human-driver preferences after observing that some manufacturers were reducing the seat track length to position the dummy unrealistically close to the instrument panel, presumably to improve crash test performance [13-14]. In any given vehicle, belt height on the dummy chest would be expected to increase as the upper anchorage and seat move upward and forward, respectively.

While prior studies have established the existence of a belt placement effect on Hybrid III sternum deflection, none has attempted to measure the effect for a range of tests. In addition to providing a more complete picture of the influence of belt placement on fleet-wide crashworthiness ratings, such a measurement could be used to adjust individual sternum deflection values to those that would be expected if all vehicles had been tested with the same belt position. These adjusted deflections could facilitate comparisons between vehicles and between test results and real-world injury outcomes. The objective of the current study was to quantify and adjust for the effect of shoulder belt placement on sternum deflection of the Hybrid III 50th percentile male dummy in the full width US NCAP and moderate overlap IIHS crash tests.

II. METHODS

Vehicle designs evaluated in the current study were those included in a separate analysis of real-world front crashes in the National Automotive Sampling System-Crashworthiness Data System (NASS-CDS) [15]. All vehicles received good ratings in the IIHS moderate overlap test. An additional inclusion requirement for the current study was the presence of a seat belt pretensioner, since this could influence which test parameters affected sternum deflection as well as the magnitude of their effects. IIHS moderate overlap (n=131) and NCAP full width tests (n=207) were analysed separately. Fewer IIHS tests were available for analysis due to the requirement for pre-test photographs, as described in the next section, Measuring Belt Position. IIHS assigns some ratings through a verification program in which manufacturers submit crash test data and the Institute periodically conducts audit tests [16]. Because manufacturers are not required to submit standardised pre-test photographs, vehicles rated through the verification program were not included in the analysis.

Measuring Belt Position

Shoulder belt placement relative to the dummy's sternum potentiometer is the main parameter of interest. However, since the potentiometer position is not evident with the dummy assembled and seated in the test vehicle, the belt position must be measured relative to some exterior dummy feature. Shoulder belt position is usually included in the pre-test clearance measurements taken as part of the NCAP test procedure. As shown in Fig. 1, the distances from a metal plate placed on the lap of the dummy to the upper and lower edges of the belt at the dummy centreline are recorded as PBU and PBL (plate-to-belt upper and plate-to-belt lower, respectively). These measurements were obtained from test reports for the vehicles being studied, but several discrepancies were noted. For some tests it appeared that the PBU and PBL values were transposed, but for others, both belt measures appeared to be exchanged with other clearance measures. In addition, photographic review of several cases suggested inconsistencies between different tests (Fig. 2). Given these considerations, and the lack of existing pre-crash belt position measurements for IIHS moderate overlap tests, a procedure for measuring the belt position using pre-test photos was developed.

Pre-test photos of the driver dummy from the front and side are available for most IIHS moderate overlap and NCAP full width tests. Figure 3 is an example case, illustrating the relevant information used for estimating the belt position, defined as NBU (nose-to-belt upper). Two different distances for scaling the photos were used: the height of the dummy's head; and the height of the target sticker marking the head centre of gravity. The head height scale was based on measurements of four different dummies owned by IIHS. Measurements taken to validate the procedure demonstrated that NBU values obtained using the dummy head height scale were more accurate than those using the target sticker scale, so this procedure was used whenever possible. When the top of the dummy's head was not visible in the front photo, the target sticker was used for scaling. In most cases, the upper edge of the belt was visible where it crossed the dummy centreline, but extrapolation was used when this position was obscured by the steering wheel or upper instrument panel. NBU could not be measured in some cases where the belt was not visible anywhere near the point where it crossed the dummy centreline. Figure 4 shows the relationship between NBU measured using pre-test photographs and measurements taken with a coordinate measurement machine (CMM) in recent IIHS tests.

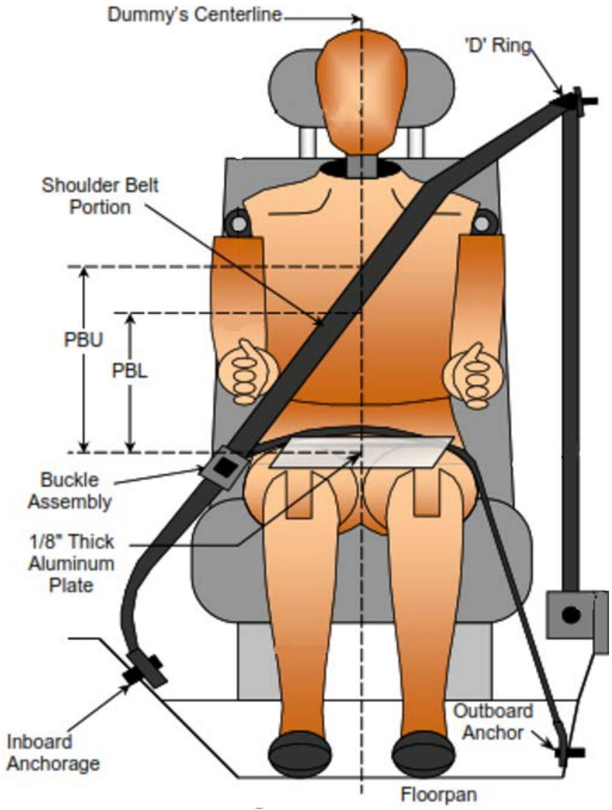

Fig. 1. Pre-test belt measurements recorded for NCAP tests.

Test 6759
Reported PBU: 340 mm

Test 5453
Reported PBU: 345 mm

Fig. 2. Example of an apparent inconsistency between recorded pre-test belt measurements and actual belt location. The PBU measurements indicate the shoulder belt in test 6759 was 5 mm vertically lower at the centreline of the dummy than in test 5453.

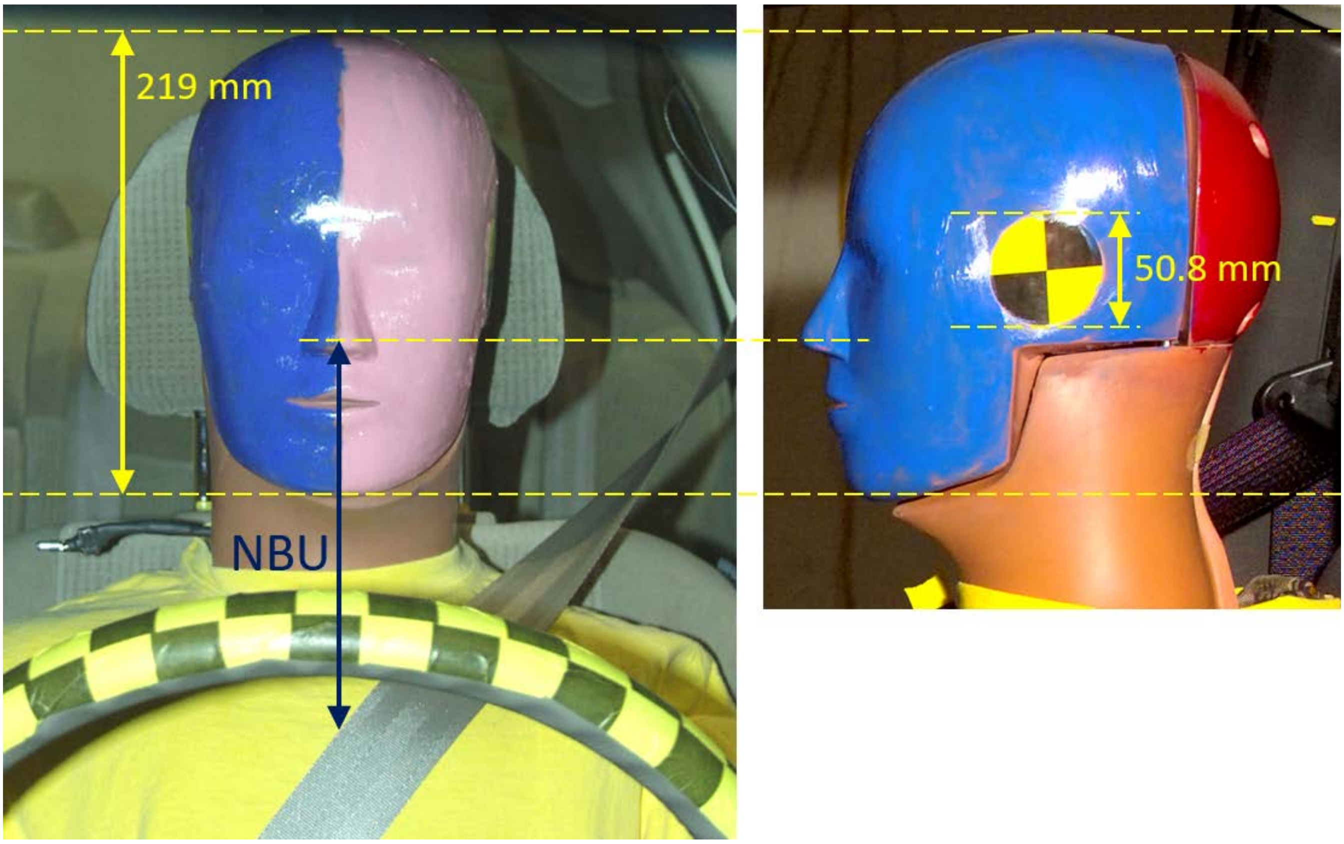

Fig. 3. Example of pre-test photographs and the scaling method used to measure the nose-to-belt upper (NBU) distance.

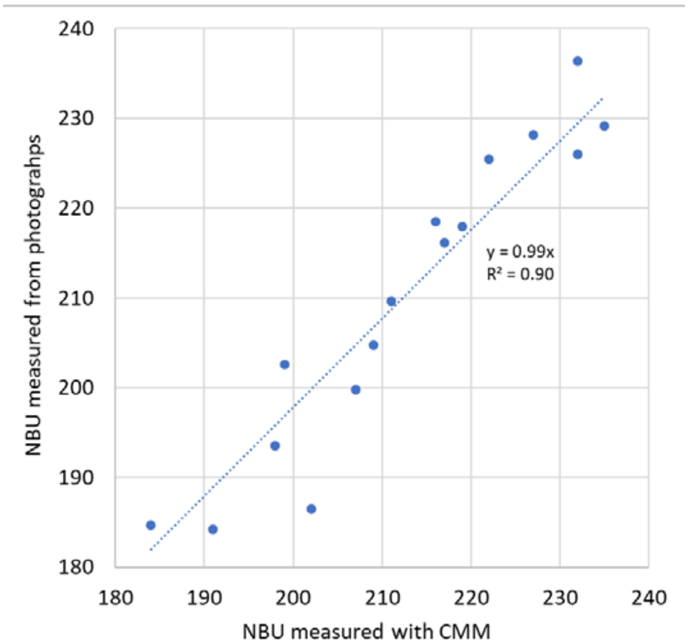

Fig. 4. Validation of photographic NBU measurements with CMM measures in recent IIHS tests. (These include some tests with the THOR 50th percentile male dummy, using the target sticker on the face instead of the Hybrid III nose.)

The NBU measurements were translated into a potentiometer-to-belt centre (PBC) measurement to facilitate calculation of the adjusted deflections as well as general interpretation of results. As outlined earlier in this section, the exact position of the potentiometer in past tests is unknown, but the geometry of the dummy allows the position to be estimated and referenced to the NBU measurements taken from pre-test photographs. For eight recent IIHS tests, CMM measurements of the dummy in its pre-test position found a range of vertical distances between the dummy nose and the clavicle access holes of 170–176 mm. Combined with measurements of the potentiometer position relative to the clavicle access holes when the dummy is partially disassembled, this produces an estimated 317 mm between the dummy nose and sternum potentiometer, on average. Assuming a belt width of 47 mm and belt angle of 45°, the centre of the belt is estimated to be directly over the sensor for an NBU of 284 mm. PBC was calculated by subtracting the NBU from 284 mm. In theory, PBC values could be negative, indicating that the belt centre was below the sternum potentiometer, but as shown in the Results section*,* below, this was never the case in practice.

Linear Regression

Linear regression was used to evaluate the effect of belt placement on peak sternum deflection. An overall estimate of the effect was established using simple linear regression. However, in order to determine whether other restraint factors confounded the effect of belt placement on sternum deflection, multiple linear regression was performed as well. The covariates of interest were measures representing the forces acting on the dummy torso, specifically those from the restraint system and the forces acting through the dummy neck and lumbar spine. The availability of such metrics varied by the test mode. There were no lumbar spine force data for the NCAP test, but preliminary models indicated that longitudinal pelvis acceleration had an effect on peak sternum deflection along with shoulder belt force and neck tension. Lumbar spine force, pelvis acceleration and shoulder belt force are typically not measured in IIHS evaluations, so only neck tension could be included in the moderate overlap sternum deflection model. Because the phasing of the restraint loads could affect the relationship between belt position and sternum deflection, peak times of the dummy metrics listed above were included as covariates and retained in the final model when they had estimated effects that were significant at the $p = 0.05$ level.

All crash test data were filtered according to SAE J211 [17]. The instantaneous peak values were used for neck tension, while the pelvis acceleration values were those sustained for at least 3 ms. Neck tension was only considered before 100 ms in the full width test and 150 ms in the moderate overlap test to capture the forces occurring during loading of the thorax. (After making these adjustments, peak neck tension occurred within 8 ms and 6 ms of peak sternum deflection, on average, in the full width and moderate overlap tests, respectively.) The various types of belt force limiters produced a wide range of belt force time-histories, with large relative differences in the timing and duration of the greatest loads. For this reason, and to avoid the influence of temporary peaks, the metric selected for analysis was the maximum force level sustained for at least 20 ms over the entire pulse.

The NCAP tests included in the current analysis were conducted by four different contractor laboratories. Preliminary data analysis revealed that systematic differences in sternum deflection values were associated with these laboratories. Analysis of the IIHS moderate overlap test data for the same vehicles did not indicate sternum deflection differences corresponding to the test facility conducting the NCAP test, suggesting the effect observed for NCAP tests is not due to actual differences in the vehicles or their restraint systems. A categorical variable representing the contracting laboratory was included as a covariate in the NCAP model to account for the possibility that these effects could confound the estimated effect of belt placement on sternum deflection.

For both the NCAP and IIHS tests, the interaction between belt placement and each covariate was estimated in separate models. Significant interaction effects would suggest that the sternum deflection adjustments could not be based on a single value for belt placement but would need to account for other factors. However, the minimum p-value for any of the interaction effects was 0.17, so no interactions were included in the final models. The final linear regression model for the NCAP test estimated the effect of belt placement on sternum deflection while controlling for shoulder belt force, neck tension, longitudinal pelvis acceleration, and test laboratory. The final model for the IIHS test estimated the effect of belt placement on sternum deflection while controlling for the magnitude and timing of peak neck tension. Pearson correlation coefficients for all included parameters are given in Table I. All regression models were calculated using the R programming language [18].

TABLE I
PEARSON CORRELATION COEFFICIENTS FOR MULTIPLE REGRESSION VARIABLES

IIHS sternum deflection model

	Neck tension	Neck tension peak time
Potentiometer-to-belt centre	0.05	0.12
Neck tension		0.03

NCAP sternum deflection model

	Shoulder belt force	Pelvis acceleration	Neck tension
Potentiometer-to-belt centre	-0.12	-0.13	-0.13
Shoulder belt force		0.18	0.27
Pelvis acceleration			0.50

Adjusted Sternum Deflections

The estimated effect of belt placement on sternum deflection in each type of crash test was used to adjust the deflections to values that would be expected if the centre of the shoulder belt crossed directly over the Hybrid III sternum potentiometer. Since none of the model interaction terms was significant, the magnitude of the adjustment depended only on the measured PBC value for each test and the estimated PBC effect from the multiple regression models. The estimated effects of the other covariates were not used in the adjustment.

III. RESULTS

Sternum potentiometer-to-belt centre (PBC) measurements for all tests included in the study are shown in Fig. 5. All measures indicated belt positions that were higher than the potentiometer, with median values in the IIHS and NCAP tests of 100 mm and 107 mm, respectively. There was a trend toward higher PBC values in the NCAP test in later years of testing. Figure 6 shows the relationship between PBC and peak sternum deflection in both tests along with the simple regression estimates. Over one-quarter of the variation in NCAP sternum deflection is explained by differences in photographically measured belt position.

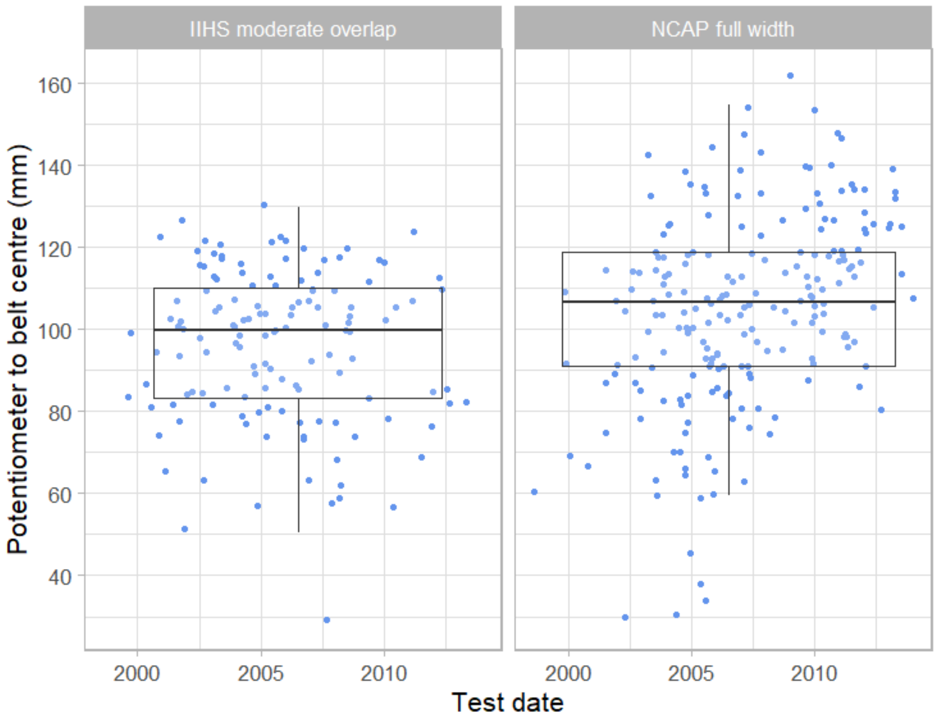

Fig. 5. Belt position measurements.

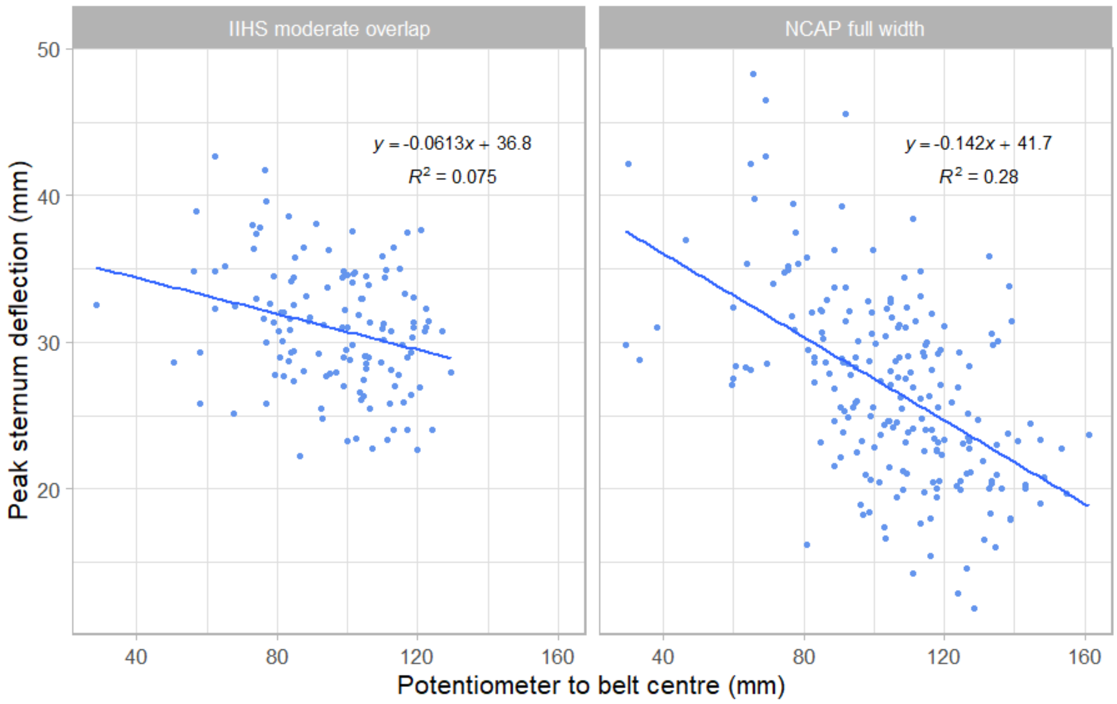

Fig. 6. Belt position measurements vs. peak sternum deflection.

The results of the multiple linear regression models for each test are shown in Table II. In both tests, the estimated effect of PBC on peak sternum deflection was statistically significant at the p = 0.01 level. In the IIHS moderate overlap test, a 1 mm vertical increase in the belt position was estimated to reduce peak sternum deflection by 0.058 mm (SE = 0.018; p = 0.002). In the NCAP full width test, the same change in belt position was estimated to reduce peak sternum deflection by 0.13 mm (SE = 0.013 mm; p < 0.001). Compared with the simple regression estimates, controlling for the other test metrics reduced the magnitude of the effect of PBC by 5–6% in both tests.

Besides belt position, increased sternum deflection in the full width test was associated with greater forces on the dummy thorax from the shoulder belt and head (through the neck) and greater pelvis deceleration. In addition, significant estimated differences in sternum deflection of up to 6 mm were associated with the laboratory conducting the test. In the moderate overlap test, increases both in the magnitude and timing of peak neck tension were associated with higher sternum deflection.

The PBC-adjusted sternum deflections are shown in Fig. 7 and compared with the deflections measured in each test. If all tests had belts centered over the sternum potentiometer, the median sternum deflection in the moderate overlap test would be expected to increase 18% to 37 mm (SE = 1.8 mm or 6%). The median value in the full width test would be expected to increase 49% to 40 mm (SE = 1.4 mm or 5%).

IV. DISCUSSION

The finding that belt position affects the Hybrid III peak sternum deflection is intuitive and well-established [6][10–12]. Previous studies isolating the influence of belt position using sled tests have found effects of similar or greater magnitude than those reported here. When converted to reduced deflection per increased PBC, Eggers *et al.* reported 0.16 mm/mm from one pair of tests [6], while Digges *et al.* reported 0.14 and 0.15 mm/mm in two pairs of tests using a 5th percentile female dummy [11]. The current study estimates were 0.06 mm/mm across the 131 moderate overlap crash tests and 0.13 mm/mm for the 207 full width tests. The presence of these effects, which remained after controlling for other test differences, demonstrates that variation in belt position is a major contributing factor to the range of sternum deflections observed across the vehicle fleet in consumer information testing. This is especially true in the full width test, where the estimated effect of belt position was over two times greater than in the moderate overlap test, and the amount of variance in sternum deflection explained by belt position alone was almost four times greater. This may be explained by the shorter, higher deceleration crash pulse of the full width test, the different longitudinal seat position, or some other factor.

TABLE II
RESULTS OF MULTIPLE REGRESSION MODELS ESTIMATING THE EFFECT OF BELT POSITION AND OTHER COVARIATES ON PEAK STERNUM DEFLECTION IN THE IIHS MODERATE OVERLAP AND NCAP FULL WIDTH TESTS

IIHS sternum deflection; $R^2_{adj} = 0.17$

Term	Estimate	Std error	p-value
Intercept	39.8		
Potentiometer-to-belt centre (mm)	−0.0580	0.0180	0.002
Neck tension (kN)	2.54	0.794	0.002
Neck tension peak time (ms)	0.0665	0.0245	0.008

NCAP sternum deflection; $R^2_{adj} = 0.57$

Term	Estimate	Std error	p-value
Intercept	30.2		
Potentiometer-to-belt centre (mm)	−0.133	0.0127	<0.001
Shoulder belt force (kN)	1.27	0.334	<0.001
Pelvis acceleration (g, positive forward)	−0.0841	0.0311	0.007
Neck tension (kN)	2.69	0.846	0.002
Test lab: Karco vs. Calspan	−2.76	0.766	<0.001
Test lab: MGA vs. Calspan	−6.41	0.836	<0.001
Test lab: TRC vs. Calspan	−3.19	1.47	0.03

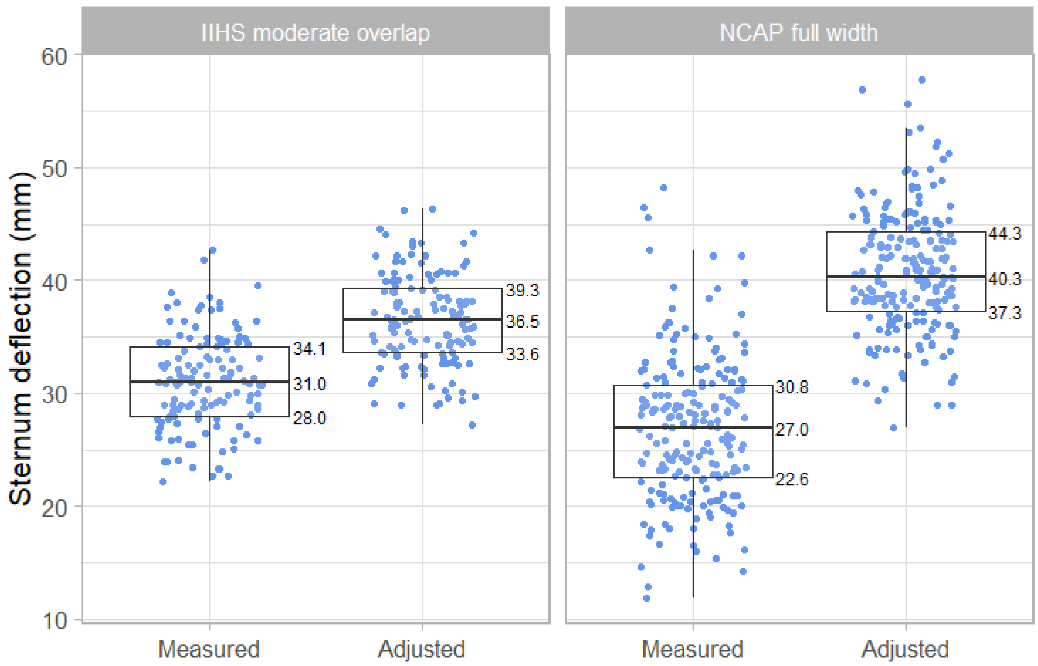

Fig. 7. Sternum deflection values measured in each test compared with the adjusted values that would be expected if the seat belt was centered over the sternum potentiometer.

Whatever the source of the differences between the two test modes, belt placements in the full width test tended to grow farther from the sternum potentiometer during a time period that corresponds with the incorporation of sternum deflection into the NCAP rating (Fig. 5). NHTSA first announced the possibility of including sternum deflection in the rating in 2004 [19]. In 2008, NHTSA finalised the procedure for 2010 model year vehicles [20], though this was later postponed for one model year [21]. For all model year vehicles in the current study, the median sternum deflection would be expected to increase from 27 mm to 40 mm with belts positioned over the potentiometer. In combination with the non-zero N_{ij} risk assigned at no load, this change alone would be sufficient to downgrade the driver rating from 5 to 3 stars without any other injury measures [20].

The IIHS moderate overlap rating procedure allows 50 mm of sternum deflection prior to any chest injury rating downgrade. The maximum sternum deflection from any moderate overlap test in the current study was 43 mm. Even after adjusting for belt position, all expected deflections remained under 50 mm, indicating that belt position did not affect the ratings of the vehicles studied. However, one possible outcome of ongoing IIHS work toward reducing the elevated risk of thoracic injury for older drivers of good-rated vehicles [15][22] is a lower sternum deflection cutoff value for rating downgrades. Should this approach be taken, the current study demonstrates the importance of controlling belt position. Even though the magnitude of the PBC effect was lower than in the full width test, it was still highly significant and could produce changes in measured deflection that affect ratings under a future protocol as well as affecting the dummy's ability to predict injury in real-world crashes.

To investigate the consequences of the belt position effect on the dummy's ability to predict injury, the adjusted sternum deflection values from the current study were used as part of a separate analysis of real-world thoracic injuries in front crashes [15]. Logistic regression was used to estimate the effect of various crash test measurements on the risk of drivers of the same vehicles sustaining a serious thoracic injury while restrained by a seat belt and airbag. After controlling for delta-V, the ability of unadjusted Hybrid III sternum deflection to predict injury was limited to certain age groups, thoracic injury types, and was apparently weakened by changes to the test procedures. Despite these limitations, adjusting the sternum deflections for belt placement did not improve the metric's injury prediction ability. Factors other than belt position differences appear to be more important in explaining the discrepancy between peak Hybrid III sternum deflection and real-world thoracic injury outcomes. This highlights a limitation of the current study: a single belt-position adjustment factor has been calculated for a range of vehicle models with different crash pulses and restraint system properties. Dealing with this limitation would require multiple tests of each vehicle with the belt in different positions to determine a vehicle-specific adjustment factor. Not only is this impractical, but an adjustment would be unnecessary if all the vehicles could be retested with the belt in the same position relative to the sternum potentiometer.

The significant and relatively large differences in NCAP deflections between test laboratories, even while controlling for belt position, suggest that there are additional factors affecting the reproducibility of Hybrid III sternum deflection measurements. The same issues may exist for the moderate overlap test, though there is less direct evidence of this. As of 2019, IIHS has conducted audit tests of 15 moderate overlap results submitted by manufacturers, with an average sternum deflection difference of 3.3 mm between the IIHS and manufacturer tests. Because the belt positions in the tests conducted by manufacturers are unknown, it is not possible to control for those differences as with the NCAP laboratories. However, the NASS-CDS study referenced in the previous paragraph found that the subset of sternum deflection data recorded at IIHS better predicted real-world injury outcomes than the full dataset, including tests conducted by manufacturers [15]. It is unknown whether the source of deflection differences between facilities is inherent to the design of Hybrid III, some other variation in how tests are conducted, or a combination of these factors.

While photographically measured belt position was a significant predictor of sternum deflection in both tests, uncertainty in the actual belt positions is a limitation of the current study. Pre-test photographs are not taken according to a strictly controlled procedure, and the resulting variation in the camera position and angles relative to the dummy as well as the focal length of the lens produce uncertainty in the measurements. While the method was validated with recent tests at IIHS (Fig. 4), this was with a relatively small number of vehicles and camera configurations that did not fully represent the range of conditions in the study dataset. The pre-test position of the shoulder belt is now recorded with a CMM in all front tests conducted at IIHS. Beyond uncertainty in the photographic measurements, differences in the number, location and aggressivity of pretensioners likely produce varying amounts of discrepancy between the actual pre-impact belt position and the position during the loading phase of the crash. It is possible that the true effect of belt position during loading could be even more predictive of sternum deflection than estimated, as well as having a somewhat different magnitude.

V. CONCLUSIONS

The position of the seat belt as measured in pre-test photographs had a strong effect on peak Hybrid III sternum deflection in NCAP full width and IIHS moderate overlap crash tests. If all belts had been centered over the sternum potentiometer, it is expected that the medium sternum deflections would have been 49% and 18% greater, respectively, than the observed values in these two test configurations.

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