DEVELOPMENT OF REAR-SEAT OCCUPANT SAFETY METRICS FOR THE MODERATE OVERLAP FRONTAL EVALUATION TEST

Marcy A. Edwards
Sushant R. Jagtap
Jessica S. Jermakian
Insurance Institute for Highway Safety
United States of America

Paper Number 23-0173

ABSTRACT

Rear seat safety advancements have lagged those in the front. To address this gap, this research aimed to develop assessment metrics to evaluate the relative protection provided by rear seat restraint systems across a series of vehicle crash tests.

Thirty-two full-scale vehicle crash tests were conducted with a Hybrid III 5th percentile female dummy seated in the left rear seating position in a 64.4 km/h, 40% offset deformable barrier test. Vehicles varied in size, class, and presence of belt pretensioners and load limiters. Dummy injury metrics for the head, neck, thorax, and femur were evaluated along with occupant kinematic metrics including head excursion and submarining. Of the 32 tests, 18 also included a pressure sensor on the rear occupant's thorax to locate the dynamic shoulder belt position.

Shoulder belt tensions ranged from 3.4 to 8.3 kN, and higher shoulder belt tensions were generally associated with higher head and neck injury values, but sternum deflection did not show a similar relationship. High (> 40 mm) and low (~20 mm) sternum deflections were observed for vehicles with and without pretensioners and load limiters and for a wide range of belt tensions. Higher dynamic belt positions were correlated with lower chest deflections and compensating for the effect of belt position aligned sternum deflections with expectations based on shoulder belt tensions. Head contact only occurred in one vehicle, but head excursion boundaries in the absence of impact remain important to ensure that restraint systems limit excursion and the risk of head injury for higher severities or larger occupants. The dummy showed propensity for submarining, an important risk factor for abdominal injuries. Femur axial forces were low for all vehicles, even in cases where the knees contacted the front seatback.

Assessment metrics were developed to evaluate the relative protection of rear occupants across a range of vehicles. A novel dummy-based metric, called the Chest Index, was developed that allows the comparison of chest protection across vehicles with a range of dynamic belt fit.

BACKGROUND

In 1995, when the Insurance Institute for Highway Safety (IIHS) began assessing occupant safety for drivers in moderate overlap frontal crashes, only 16% of the vehicles rated received a good overall rating. By 2008, all new U.S. cars were equipped with pretensioners and load limiters for front-seat occupants and by 2013, all vehicles rated received a good overall rating in this test. The benefits of better performance in the moderate overlap crash test are evident in field data, where drivers of vehicles rated good in this test are 46% less likely to die in a frontal crash than drivers of poor-rated vehicles [1]. Similarly, an analysis of U.S. New Car Assessment Program (U.S. NCAP) frontal test scores found a correlation between composite scores and fatality rates for belted drivers in collisions during 1979–1991 [2]. Frontal crash test programs have historically prioritized reducing injuries for drivers due to their higher occupancy rates, which has led to a lag in rear-seat occupant safety to the point that the rear seat is now considered less safe than the front, especially for older adults [3]. In 2015, the European New Car Assessment Programme (Euro NCAP) introduced occupant safety ratings for rear-seat occupants in frontal crashes, which resulted in almost all European vehicles being equipped with pretensioners and load limiters by 2020, but until recently, U.S. crash tests conducted under Federal Motor Vehicle Safety Standards (FMVSSs), the U.S. NCAP, and IIHS have not evaluated occupant safety for rear-seated occupants in frontal crashes [4].

Rear-seat injuries differ from front-seat injuries due to the wide range of occupant sizes and restraint environments (e.g., no airbags or knee bolsters and belt-anchorage variability). In 2003, Parenteau and Viano found that primary Abbreviated Injury Scale (AIS) 3+ injuries for restrained rear-seated adults and teens in frontal crashes were to the thorax (78%), head (9%), lower extremities (8%), and abdomen (5%) [5]. Primary AIS 3+ injuries for children ages 4–12 years old were to the head (30%), upper and lower extremities (33% and 20%), and abdomen (10%) [6]. In 2019, Jermakian et al. studied rear-occupant injuries and causation scenarios in frontal crashes in the National Automotive Sampling System-Crashworthiness Data System (NASS-CDS) and from police –reported crash records in the Fatality Analysis Reporting System (FARS). This study documented the chest, head, and abdomen as the most common injuries in both datasets and documented shoulder belt loading, head impacts with the interior, and lap belt submarining as the most common injury causation scenarios for these injuries, respectively [7].

To address the gap in protection for rear-seat occupants, IIHS has examined whether to include a rear-seated dummy in its frontal crashworthiness evaluations. Initial research studied various crash modes, human surrogates, and occupant positions and found that the 40% offset deformable frontal crash test (64.4 km/h) with an H3-5F dummy seated in the left second-row seating position provided the best opportunity to represent the rear-occupant injuries observed in field data [8]. However, dummy limitations affect the alignment between crash test results and real-world outcomes. Kuppa et al. studied rear-seat occupant injuries from both field studies and anthropomorphic test devices (ATDs) and found that while real-world occupant injuries indicated the thorax as the most frequently injured body region, the ATDs reported the head and neck as the most seriously injured body region [9]. Other researchers have observed issues specifically with the sternum deflection metric on the Hybrid III 5th percentile female (H3-5F) dummy, indicating a sensitivity to belt position that could affect dummy outcomes [10,11,12]. Edwards et al. confirmed this sensitivity and quantified its relationship with belt position for the H3-5F with sled testing [13]. Assessing the safety performance of vehicle restraint systems with metrics that can both faithfully represent the injuries observed in real-world crashes and reliably differentiate performance is important to encourage meaningful improvements in rear-seat occupant safety in frontal crashes. This research aimed to address the known shortcomings with ATDs and develop reliable assessment metrics to evaluate the protection from head, neck, chest, abdomen, and lower extremity injury provided by rear-seat restraint systems in 64 km/h, 40% offset deformable barrier (ODB) vehicle crash tests.

METHODS

Thirty-two full-scale frontal vehicle crash tests were conducted with a H3-5F seated in the second-row left-seating position and a 50th percentile male dummy (THOR-50M or H3-50M) in the driver seat in the IIHS moderate overlap test condition, where 40% of the width of the vehicle impacts a deformable, aluminum honeycomb barrier at 64.4 km/h. Vehicles tested varied in class and rear seat-belt restraint technology. A complete test matrix is shown in Table 1.

The IIHS *Dummy Seating Procedure for Rear Outboard Positions, Version II* [14] was used to position a H3-5F dummy in the left second-row seating position. The IIHS procedure described in *Guidelines for Using the UMTRI ATD Positioning Procedure for ATD and Seat Positioning, Version V* [15], was used to position both the THOR-50M and H3-50M dummies in the driver seat. After the seat was set using the H3-50M dummy, the seat was not moved in the process of positioning THOR-50M. Thus, the seat position was the same for all the tests, regardless of which dummy was in the front seat.

The H3-5F dummy metrics included triaxial head accelerations and angular rates; thorax triaxial accelerations, y-axis angular rate, and sternum potentiometer deflection; pelvis x- and z-axis accelerations and y-axis angular rate; upper neck, lower neck, thoracic spine, and lumbar spine x- and z-axis forces and y-axis moments; left and right anterior superior iliac spine (ASIS) x-axis forces and y-axis moments; and femur axial forces. Instrumentation also included shoulder and outboard lap-belt load cells. All dummy and vehicle sensor data were collected at a sampling rate of 10,000 Hz in accordance with the SAEJ211 coordinate system [16].

To gather additional information on shoulder belt position and loading on the thorax, a thin high-frequency, high-resolution pressure mat (XSensor, Calgary, Canada) was also included in 18 tests to provide contact locations and pressures between the shoulder belt and thorax. The pressure sensor mat provided time-dependent, two-dimensional mapping of the pressures between the seat belt and thorax at a frequency of 3900 Hz and a resolution of 5 mm x 15 mm for the belt-shaped sensor (XSensor belt, HX210:30.40.05-15M HSS) (Figure 1a) and 3300 Hz and a resolution of 5 mm x 5 mm for the vest-shaped sensor (XSensor vest, XSensor HX210:36.48.05M-HSS) (Figure 1b). Three of the 18 tests employed the belt-shaped sensor, and the remainder used a vest-shaped sensor fitted to the anterior chest of the H3-5F. The pressure mat was secured using adhesive tape on all sides to prevent migration of the sensor relative to the flesh. The location of the pressure mat was quantified relative to ATD landmarks with a 3D coordinate measurement machine (CMM) in a dummy-based coordinate system prior to the test according to the IIHS *Moderate Overlap Frontal Crashworthiness Evaluation 2.0 Crash Test Protocol (Version I)* [17], so that belt placement could be related to the sternum potentiometer location. For this measurement, individual sensor rows and columns were mapped prior to testing using a CMM, so row and column positions at the belt centerline could be mapped to the dummy-based coordinate system. The vertical distance from the centerline of the belt path relative to the sternum potentiometer was then calculated using a linear equation representing the belt path and sternum potentiometer coordinates according to the IIHS *Moderate Overlap Crashworthiness Evaluation 2.0 Rating Guidelines (Version I)* [18].

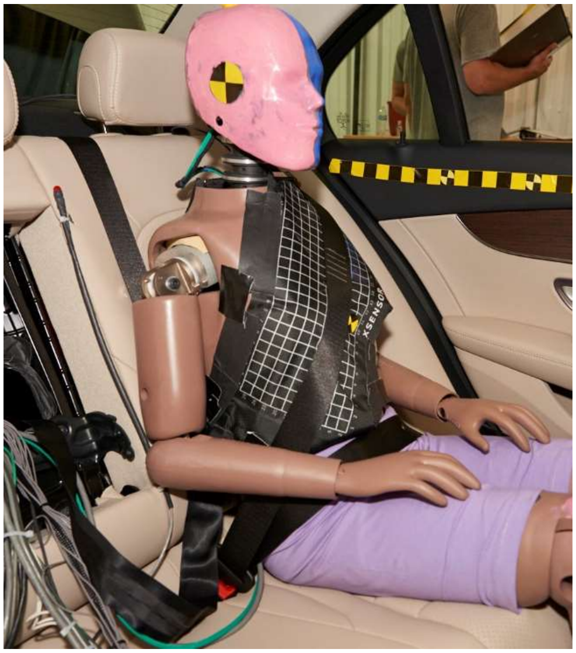
Figure 1a. Belt sensor


Figure 1b. Vest sensor

Head excursion for the rear occupant was measured via video analyses. Vertical tapelines were applied on the left rear door at locations corresponding to the pre-impact position of the rearmost point on the front seatback in test position and 50 mm rearward of the front seatback. Head excursion was measured in four segments: (1) rearward of the 50-mm line, (2) between the 50-mm line and the front seatback, (3) beyond the front seatback line, and (4) contact with the front seatback.

In this research series, submarining was evaluated primarily with video analysis of the belt position. However, the H3-5F is also equipped with ASIS load cells that measure both load on the ASIS and moment about the lateral axis at the center of the ASIS, which provides information on whether the belt is loading the top or bottom of the ASIS. These sensors, along with lap belt load, were used to confirm findings observed in the video analysis.

Table 1.
Test matrix of full-scale vehicle crash tests conducted at 64.4 km/h into a deformable barrier at a 40% overlap

Rear occupant seat belt design	Vehicle tested	Vehicle class	Test ID	Belt position measurement
Standard belt	2021 Chevrolet Equinox	Small SUV	CEF2116	XSensor vest
	2021 Hyundai Tucson	Small SUV	CEF2104	XSensor vest
	2021 Jeep Compass	Small SUV	CEF2117	XSensor vest
	2022 Mitsubishi Eclipse Cross	Small SUV	CEF2107	XSensor vest
	2020 Hyundai Santa Fe	Midsize SUV	CF19031	None
	2018 Mazda 6	Midsize car	CF19026	None
	2019 Chevrolet Equinox	Small SUV	CF19027	None
	2021 Jeep Renegade	Small SUV	CEF2118	XSensor vest
	2021 Buick Encore	Small SUV	CEF2103	XSensor vest
	2021 Honda CR-V	Small SUV	CEF2115	XSensor vest
	2021 Honda HR-V	Small SUV	CEF2111	XSensor vest
	2020 Kia Rio	Minicar	CF21010	XSensor belt
	2020 Toyota Yaris	Minicar	CF21006	None
	2017 Honda Civic	Small car	CF19028	None
	2017 Chrysler Pacifica	Minivan	CF19029	None
	2020 Chevrolet Colorado	Small pickup	CF21011	None
	2021 Mazda CX-5	Small SUV	CEF2109	XSensor vest
Load limiter belt	2018 Volkswagen Atlas	Midsize SUV	CF19024	None
Pretensioner and load limiter belt	2021 Volvo XC40	Small SUV	CEF2108	XSensor vest
	2021 Nissan Rogue	Small SUV	CEF2112	XSensor vest
	2020 Nissan Sentra	Small car	CF21007	None
	2020 Mercedes-Benz C 300	Midsize luxury car	CF21008	XSensor belt
	2019 Volvo XC60	Midsize luxury SUV	CF19023	None
	2019 Nissan Altima	Midsize car	CF19025	None
	2021 Toyota RAV4	Small SUV	CEF2110	XSensor vest
	2021 Ford Escape	Small SUV	CEF2114	XSensor vest
	2021 Audi Q3	Small SUV	CEF2105	XSensor vest
	2019 Volvo XC60 (Dual LL)	Midsize luxury SUV	CF19032	None
	2020 BMW 3 series	Midsize luxury car	CF21009	Xsensor belt
	2020 Ford Escape	Small SUV	CF19033	None
	2021 Subaru Forester	Small SUV	CEF2113	XSensor vest
	2020 Subaru Forester	Small SUV	CF19030	None

This paper discusses results for shoulder belt tension, head injury criterion, resultant head acceleration, head excursion, upper neck tension, upper neck compression, Nij, sternum deflection, the influence of belt position on sternum deflection, submarining (migration of the lap belt into the abdomen) and femur axial compression. However, more dummy metrics were evaluated than will be discussed in this paper. In addition to upper neck tension, upper neck compression, and Nij, upper neck flexion and extension moments were also evaluated. Peak moment values, particularly extension moment, often were recorded after the forward loading phase of the event. Since the biofidelity of the dummy kinematics for the H3-5F for rebound are uncertain, these values are a lower priority than those measured during the loading phase. Resultant thoracic acceleration was also considered for evaluation but excluded because it "sums the effects of force inputs from the ribcage, shoulder and arms, abdomen, neck and lumbar spine," which does not necessarily represent the rib cage compression injuries that cause rib fracture and organ injury [19]. Sternum deflection rate and viscous criterion were also evaluated, but closely followed the trends of sternum deflection so were not considered further.

Metrics were evaluated for both their prediction of injury compared to field observations and their correlations with expected beneficial technology, like shoulder belt tension, and with potential confounding factors like belt position (Table A2, Appendix).

RESULTS

Seat belt technology in the rear seat

Of the 32 vehicles tested, 17 had standard belts, 1 had only load limiters, and 14 had both pretensioners and load limiters. Shoulder belt tensions for standard belts ranged from 6.0 to 8.3 kN and ranged from 3.4 to 5.5 kN for the pretensioning and load-limiting belts (Table A1, Appendix). The one belt with only a load limiter had a shoulder belt tension of 6.4 kN. All belts with pretensioners and load limiters had shoulder belt tensions under 6.0 kN, and all standard belts had shoulder belt tensions of 6.0 kN or higher. Rear-seat pretensioning and load limiting for all vehicles equipped were exclusively in the shoulder belt retractor.

Head Injury

Two injury metrics, head injury criterion calculated over a 15-ms interval (HIC 15) and peak resultant head acceleration, were used to assess risk of head injury for the rear occupants. HIC criterion and peak resultant head acceleration are both meant to assess the risk of skull fracture from hard contacts. In this test series, the dummy contacted the interior structure (front seatback) in only one test; the extended cab CF21011 Colorado, which had the smallest rear-occupant space of all the vehicles tested. Though no head contact with the seatback occurred in any of the other vehicles, in some cases, the front seatback pivoted away from the rear occupant in phase with the excursion of the rear-seat occupant's head. In Figure 2a, the pre-impact, rearmost point of the front seatback is marked on the left rear door by the leading edge of the most forward vertical tape line. In Figure 2b, the same vehicle is shown 110 ms after impact. At this time, the front seatback has moved forward from the original position and, though the head crosses the boundary for the original position of the seatback, it still does not contact the front seatback.

Figure 2a. Pre-impact photo showing the front edge of the vertical tapeline positioned at the rearmost point of the front seatback

Figure 2b. Photo at 110 ms showing the front seatback moving in phase with the rear-seat occupant's excursion

To evaluate the risk of head impacts in the absence of contact with the front seatback, measurements were taken of the head relative to the pretest position of the seatback. Figure 3 shows the rear-seat occupant's head excursion for each vehicle relative to the front seatback. The head impacted the seatback in 1 vehicle, crossed the pre-impact seatback line in 3 vehicles, came within 50 mm of the pre-impact seatback line in 13 vehicles, and remained farther than 50 mm from the pre-impact seatback line in 15 vehicles. The 4 vehicles where the head either contacted the seatback or crossed the seatback line all had standard rear-occupant belts and of these, 2 were small SUVs, 1 was small pickup with an extended cab, and 1 was a minicar.

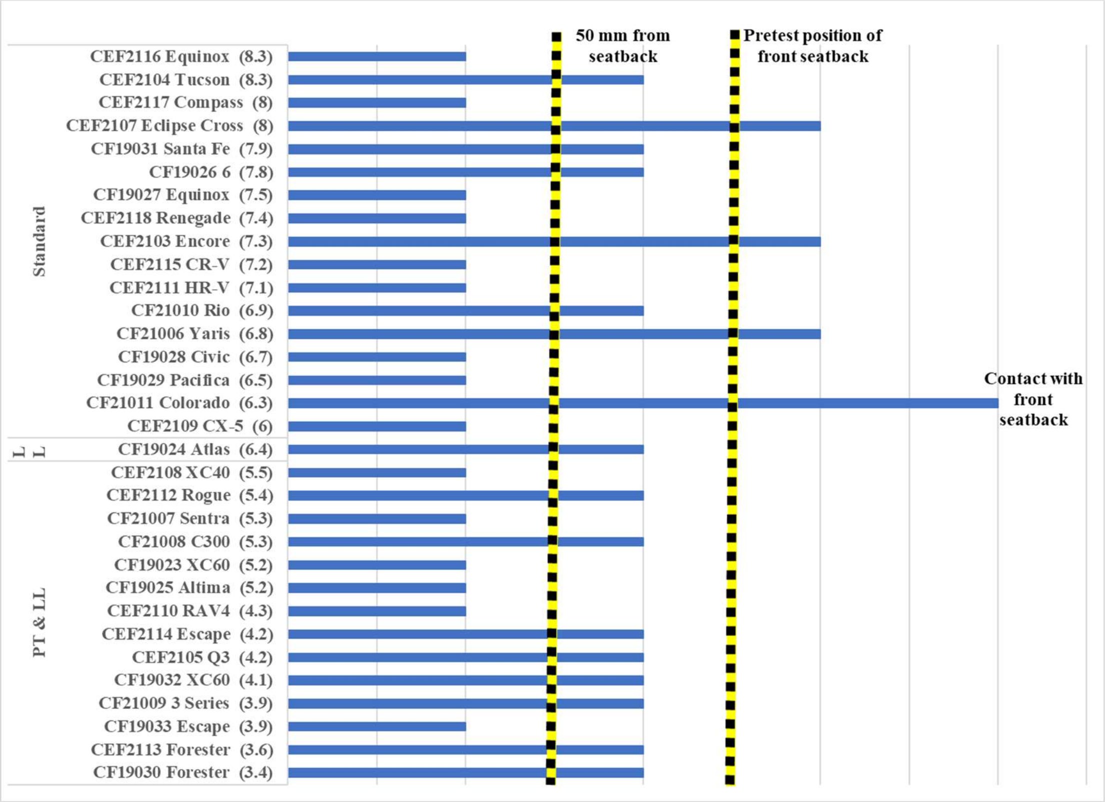

Figure 3. Rear-occupant head excursion categories (relative to the front seatback). Vehicle tests are organized by rear seat-belt type (standard, load limiter only [LL], and pretensioner and load limiter [PT & LL]) and ordered by shoulder belt tension (kN).

Figure 4 shows both normalized HIC 15 and peak resultant head acceleration. Peak resultant acceleration values ranged from 66 to 106 g for standard belts and 49 to 74 g for belts with pretensioners and load limiters. Peak resultant head acceleration reported its highest value (106 g) in the one vehicle where the occupant's head impacted the vehicle interior. HIC 15 values ranged from 433 to 1393 for standard belts and 222 to 598 for belts with pretensioners and load limiters. HIC 15 reported its highest value (1393) in the vehicle with the highest shoulder belt tension. Both HIC 15 and peak resultant head acceleration had positive correlations (r = .85 and 0.81, respectively) with shoulder belt tension.

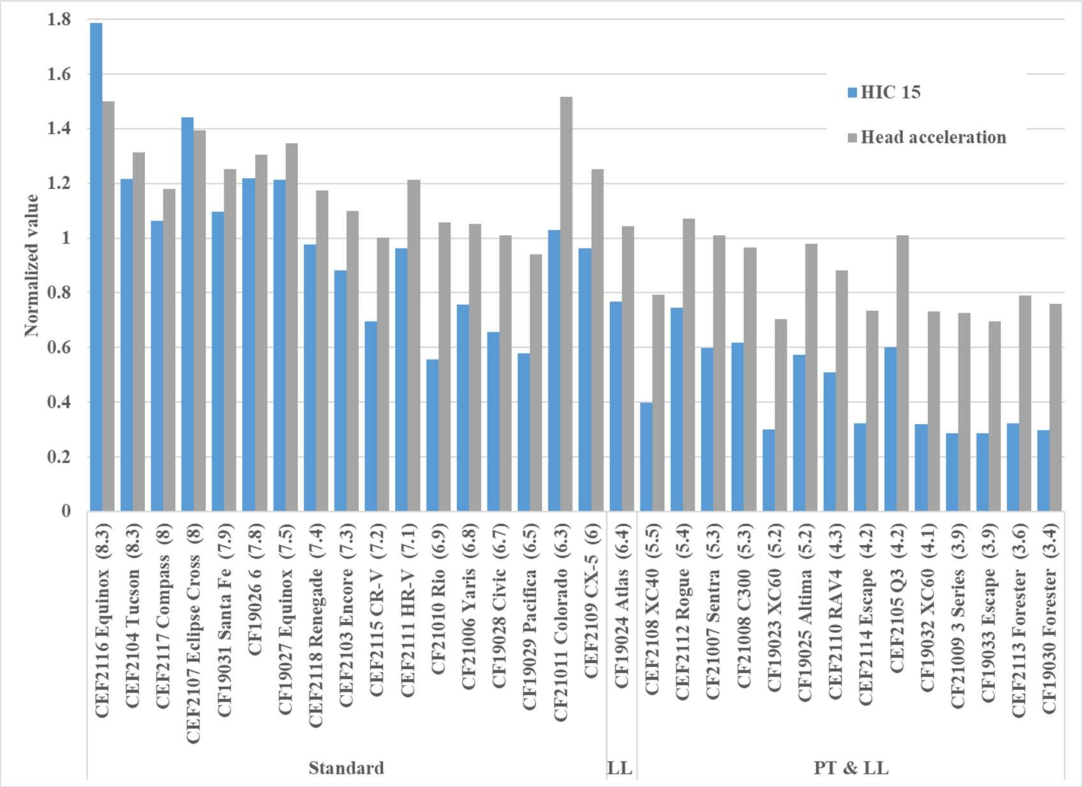

Figure 4. HIC 15 and resultant head acceleration normalized by the reference values 779 and 70 g, respectively. Vehicle tests are organized by rear belt type (standard, load limiter only [LL], and pretensioner and load limiter [PT &LL]) and ordered by shoulder belt tension (kN).

Neck Injury

Three injury metrics were evaluated for assessing the risk of neck injury for rear occupants: upper neck tension, upper neck compression, and maximum Nij (Figure 5). Peak neck tensions and maximum Nij values occurred primarily during the loading phase of the crash, while peak compression values occurred primarily during rebound. Peak neck-tension values ranged from 1.6 to 4.3 kN for standard belts and 1.6 to 3.2 kN for belts with pretensioners and load limiters. Fourteen of the 32 tests had neck tensions that exceeded the Injury Assessment Reference Value (IARV) of 2.6 kN for in-position occupants [20]. Peak neck compression values ranged from 0 to 0.7 kN for standard belts and 0 to 0.6 kN for belts with pretensioners and load limiters. None of the peak compression values exceeded the 2.5 kN IARV (Mertz, 2016). Peak Nij values ranged from 0.7 to 1.3 for standard belts and 0.5 to 0.9 for belts with pretensioners and load limiters, all of which were recorded during the loading phase and included the tension component.

Both neck tension and maximum Nij had positive correlations (r = .76 and .74, respectively) with shoulder belt tension, indicating that the restraint system affects neck forces during loading. Neck compression, however, had no correlation with shoulder belt tension (r =.1). Further, correlations between neck tension and HIC 15 were high (r = .88) for noncontact cases, indicating that both metrics are similarly reporting the effect of the restraint system forces on the occupant.

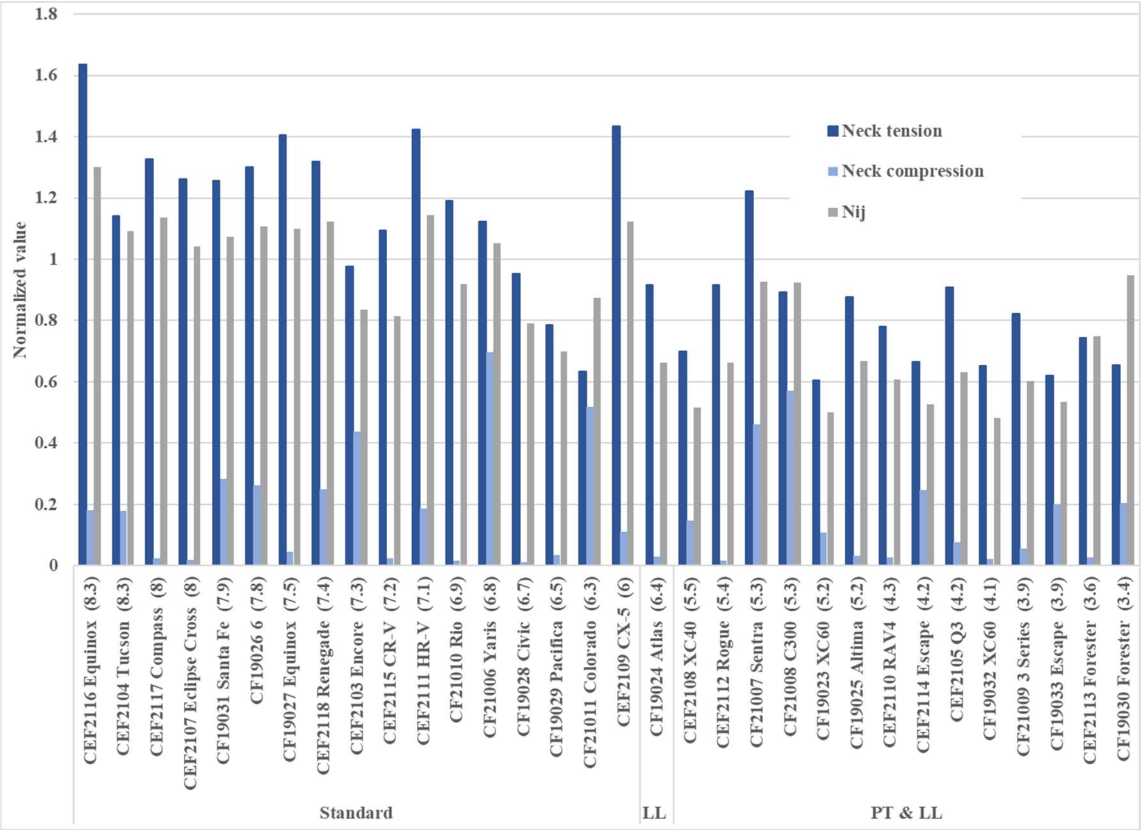

Figure 5. Neck tension, neck compression and Nij values normalized by 2.1 kN, 2.5 kN and 1.0, respectively. Vehicle tests are organized by rear belt type (standard, load limiter only [LL], and pretensioner and load limiter [PT &LL]) and ordered by shoulder belt tension (kN).

Figure 6 shows the correlation between neck tension and maximum Nij plotted with their respective IARVs. Because of the mostly linear nature of the relationship between these two metrics, there are no tests where maximum Nij exceeds the IARV, but neck tension does not. However, there are two tests where max Nij does not align with the linear relationship with neck tension and maximum Nij reports a higher normalized value than neck tension, the CF19030 Forester and CF21011 Colorado. In these two tests, Nij tension-extension, rather than tension-flexion, reported the highest value during the loading phase of the event. The CF21011 Colorado was the one vehicle where the head impacted the front seatback, which reduced neck tension but increased extension moment (Figure 7). The CF19030 Forester had the lowest shoulder belt tension in the test series, which also reduced neck tensions but resulted in alternate head-neck kinematics that increased neck extension during the loading phase of the event.

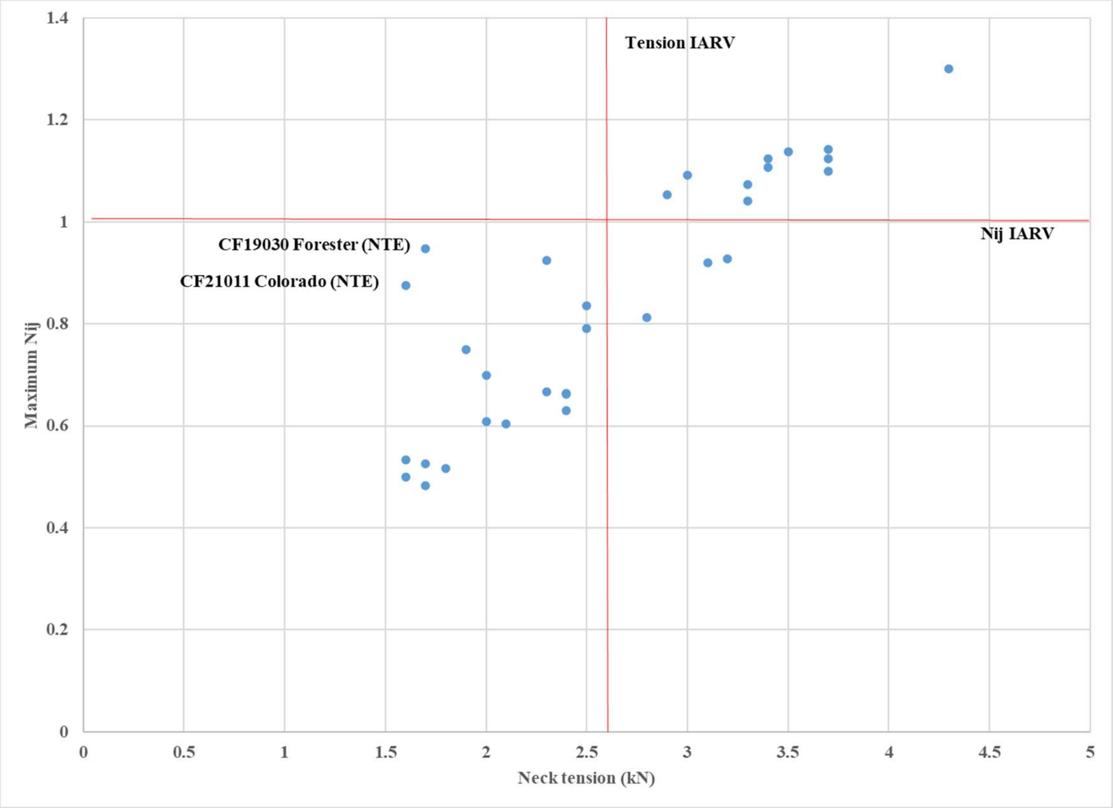

Figure 6. Correlation of neck tension to maximum Nij plotted with IARVs

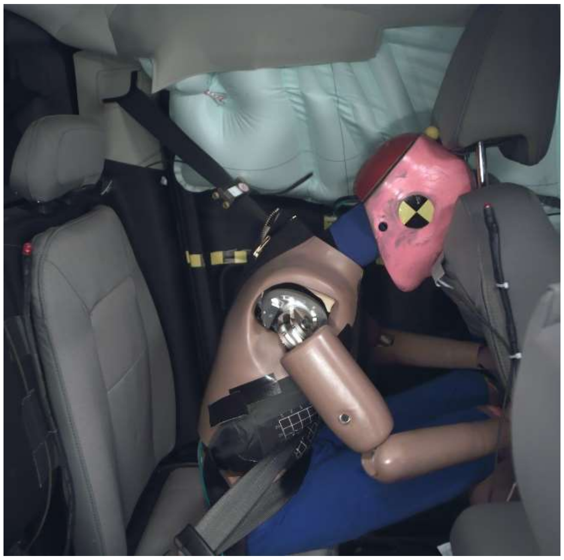

Figure 7. CF21011 Colorado at 100 ms

Chest Injury

Sternum deflection was the only metric evaluated for assessing the risk of chest injury for rear occupants. Sternum deflection provides information about the loads sustained directly to the rib cage, which are the source of many life-threatening organ injuries. Figure 8 shows peak sternum deflection values. Peak sternum deflection values ranged from -43 to -20 mm for standard belts and -41 to -20 mm for belts with pretensioners and load limiters. Only three of the tests had sternum deflections that exceeded the IARV of -41 mm (Mertz, 2016).

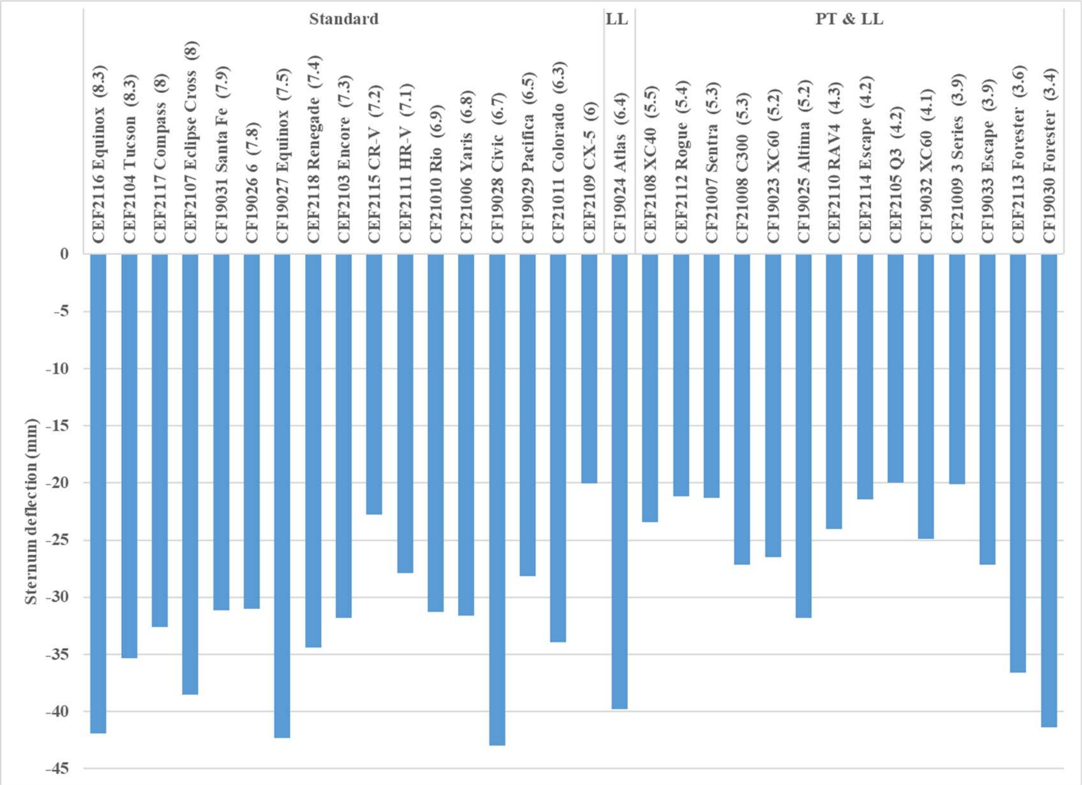

Figure 8. Peak sternum deflection values. Vehicle tests are organized by rear belt type (standard, load limiter only [LL], and pretensioner and load limiter [PT &LL]) and ordered by shoulder belt tension (kN).

Video analysis of the first 14 tests in this data series showed a wide range of pretest belt positions and factors like belt pretensioning and the lap belt migrating over the ASIS into the abdomen sometimes caused greater shoulder belt movement on the chest (Figure 9). Figure 10 shows the relationship between and variation in pretest static belt positions and dynamic belt positions at the time of maximum sternum deflection for the 18 tests with a pressure mat. Static belt positions ranged from 40 to 80 mm above the sternum potentiometer, a range of 40 mm. Dynamic belt position ranged from 48 to 129 mm above the sternum potentiometer, a range of 81 mm. Static belt positions show some relationship with dynamic belt positions (r = 0.68), but the wide range of dynamic results for a given static position show that static position is not a good predictor of dynamic position. Figure 11 shows the examples of the lowest and highest dynamic belt positions. Belt positions above 110 mm mostly loaded the neck rather than the shoulder.

Figure 9a. CF19023 (XC60) Pre-impact belt position

Figure 9b. CF19023 (XC60) belt position after pretensioning

Figure 9c. CEF2109 (6) Pre-impact belt position

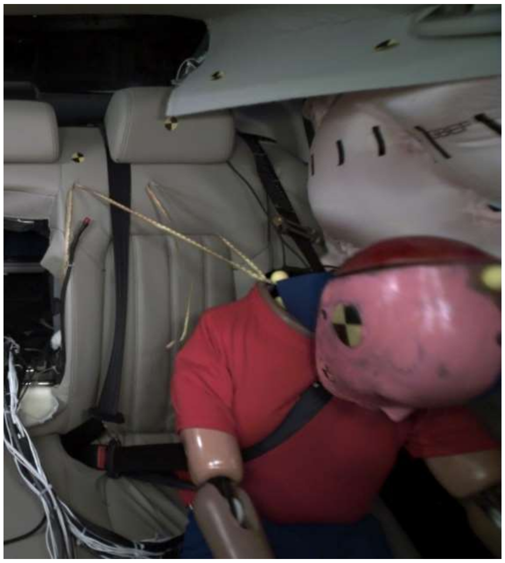

Figure 9d. CEF2109 (6) belt position @ maximum excursion

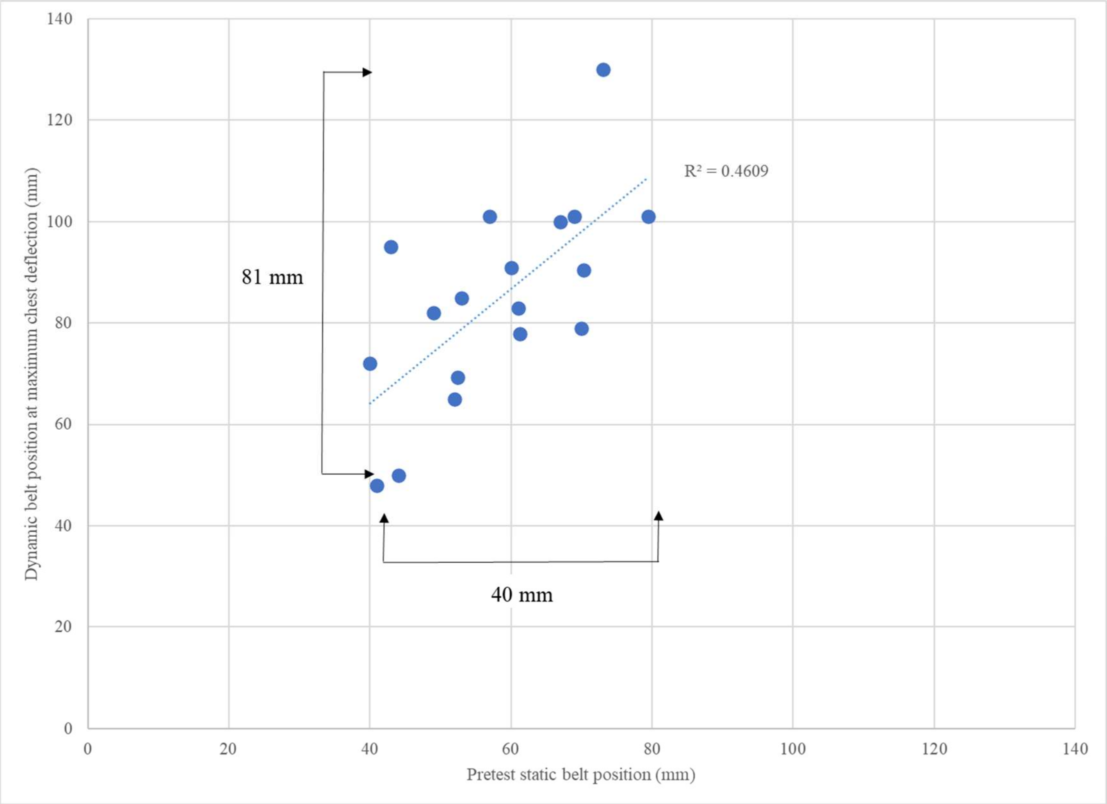

Figure 10. Belt positions relative to sternum potentiometer at pretest and maximum chest deflection.

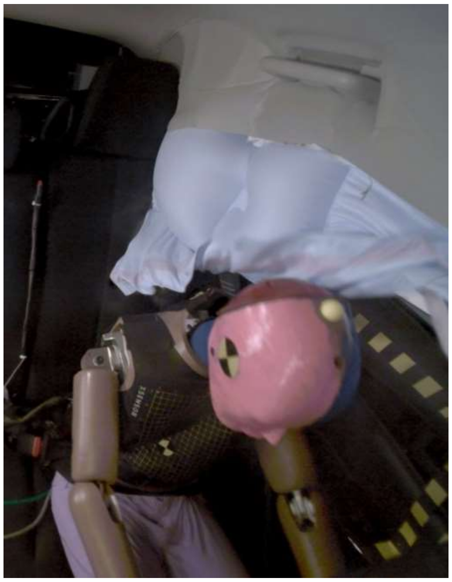

Figure 11a. Lowest dynamic belt position (104 ms); CEF2107 (Eclipse Cross)

Figure 11b. Highest dynamic belt position (120 ms); CEF2115 (CR-V)

Figure 12 shows the relationship between sternum deflection and both shoulder belt tension and dynamic belt position for the 18 tests where belt position could be measured. In the complete 32 test dataset, shoulder belt tension explained only 19% (r = .44) of the variance in sternum deflection values. The correlation between sternum deflection and shoulder belt tension was slightly higher in the smaller (18 test) dataset (r =.62) where belt position could be measured. Conversely, the correlation between sternum deflection and dynamic belt position was high (r = .75), indicating that dynamic belt position influenced sternum deflection more than belt tension. Shoulder belt tension and dynamic shoulder belt position were not highly correlated (r = .13), so their effect on sternum deflection was largely independent.

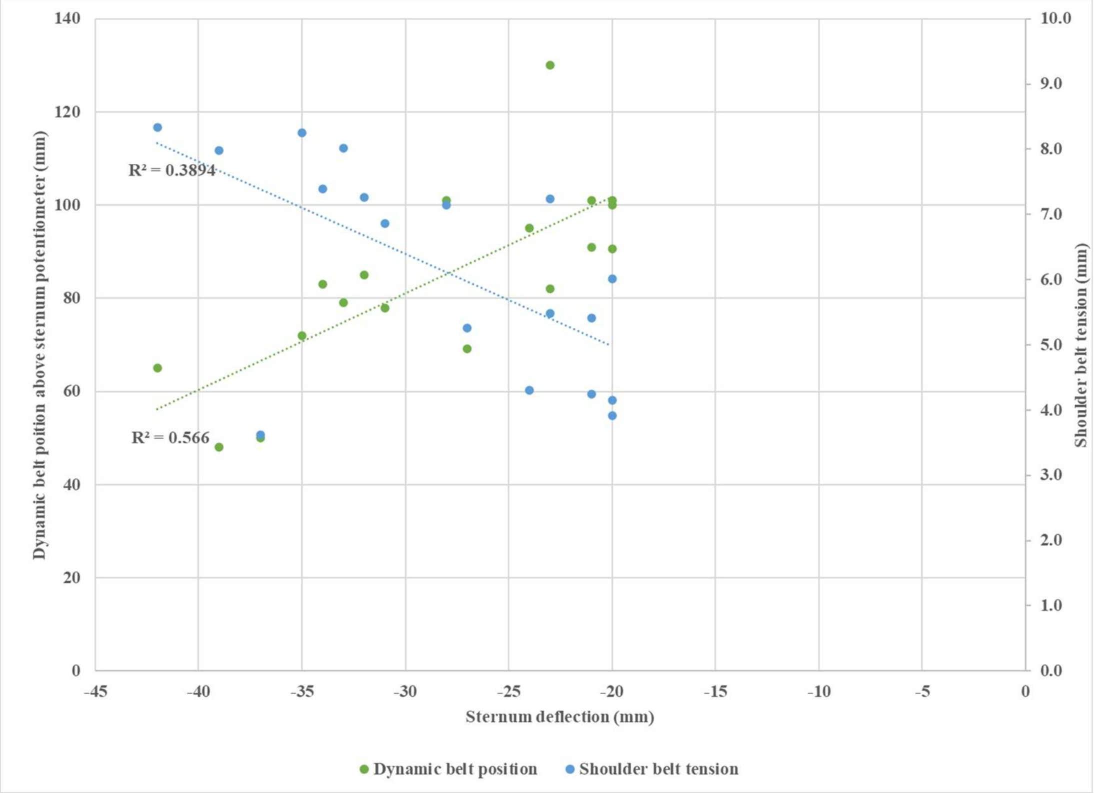

Figure 12. Correlation of sternum deflection to belt position and shoulder belt tension

Edwards et. al studied the sensitivity of the H3-5F sternum deflection measurement to belt position in the rear-seat environment and found the linear relationship of a 0.5% reduction in sternum deflection per millimeter of vertical distance from the sternum potentiometer [13]. In the current study, this sensitivity was used to compensate the sternum deflection outputs in each test for the effect of belt position. This calculation, called Chest Index (Equations 1 and 2), predicts what the sternum deflection would have been for a given vehicle and restraint environment without the influence of shoulder belt position. The calculation predicts the sternum deflection with a belt located on the third rib, which is 17 mm above the sternum potentiometer ball location on the uncompressed thorax. Chest Index is meant to provide a fair comparison between restraint systems regardless of the belt position on the chest, but because it is a departure from the sternum deflection output of the sensor, it does not relate to injury risk curves that have been established for sternum deflection for the H3-5F dummy.

Chest Index Calculation

$$\begin{aligned}&Predicted\ percent\ change\ in\ sternum\ deflection\ (Pchange)\\&= 0.5\% \times (dynamic\ belt\ position - 17)\end{aligned}$$ **Equation (1)**

$$Chest\ Index = \frac{|Measured\ sternum\ deflection|}{\left(1 - \left(\frac{Pchange}{100}\right)\right)}$$ **Equation (2)**

Constant	Definition
0.5%	Reduction in sternum deflection per 1-mm increase in belt position (Edwards et al., 2022).
17 mm	Position of rib 3 relative to the sternum pot ball on the H3-5F dummy's uncompressed thorax.
Dynamic belt position	Vertical distance from the sternum pot ball on the H3-5F dummy's uncompressed thorax to the centerline of the shoulder belt at the time of maximum sternum deflection.
Measured sternum deflection	Maximum value measured by the sternum potentiometer on H3-5F dummy.

Figure 13 shows the results for the Chest Index calculation for each vehicle where the dynamic belt position could be measured along with the original sternum deflection values. Since all the shoulder belt positions were higher than 17 mm (the Chest Index belt-reference point), the Chest Index value increased compared with the sternum deflection value. Unlike sternum deflection that had almost an identical range of results for belts with and without pretensioning and load-limiting technology, Chest Index ranged from 34 to 56 for shoulder belts without this technology and from 32 to 44 for belts with this technology, and, with the exception of one vehicle, all values for standard belts were higher than all values for belts with this technology. Further analysis of the correlation between Chest Index and both shoulder belt tension and dynamic belt position (Figure 14) shows that Chest Index has a higher correlation (r = .8) with shoulder belt tension than sternum deflection (r = .62). In addition, whereas sternum deflection had some relationship with dynamic belt position (r = .75), Chest Index shows no relationship with dynamic belt position (r = 0.46) (Figure 14).

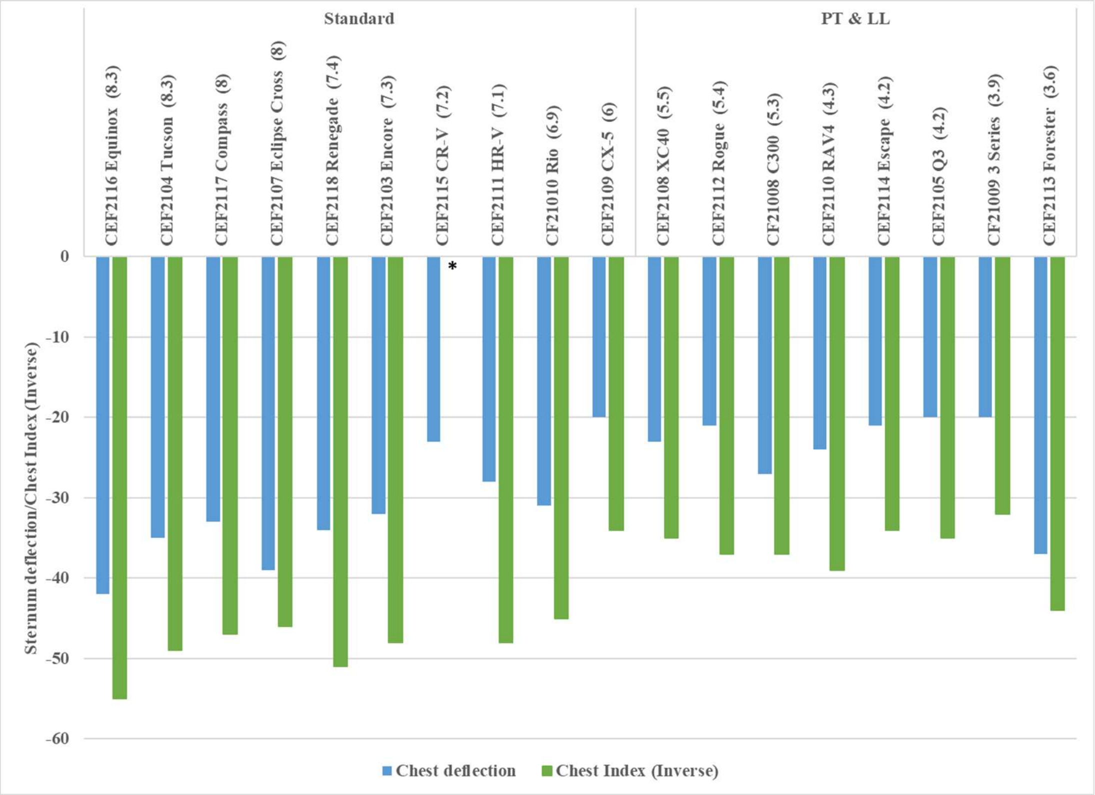

Figure 13. Chest Index (inverted for plot) and sternum deflection values. Vehicle tests are organized by rear belt type (standard, load limiter only [LL], and pretensioner and load limiter [PT & LL]) and ordered by shoulder belt tension (kN). *Indicates test where belt position was too high to calculate Chest Index

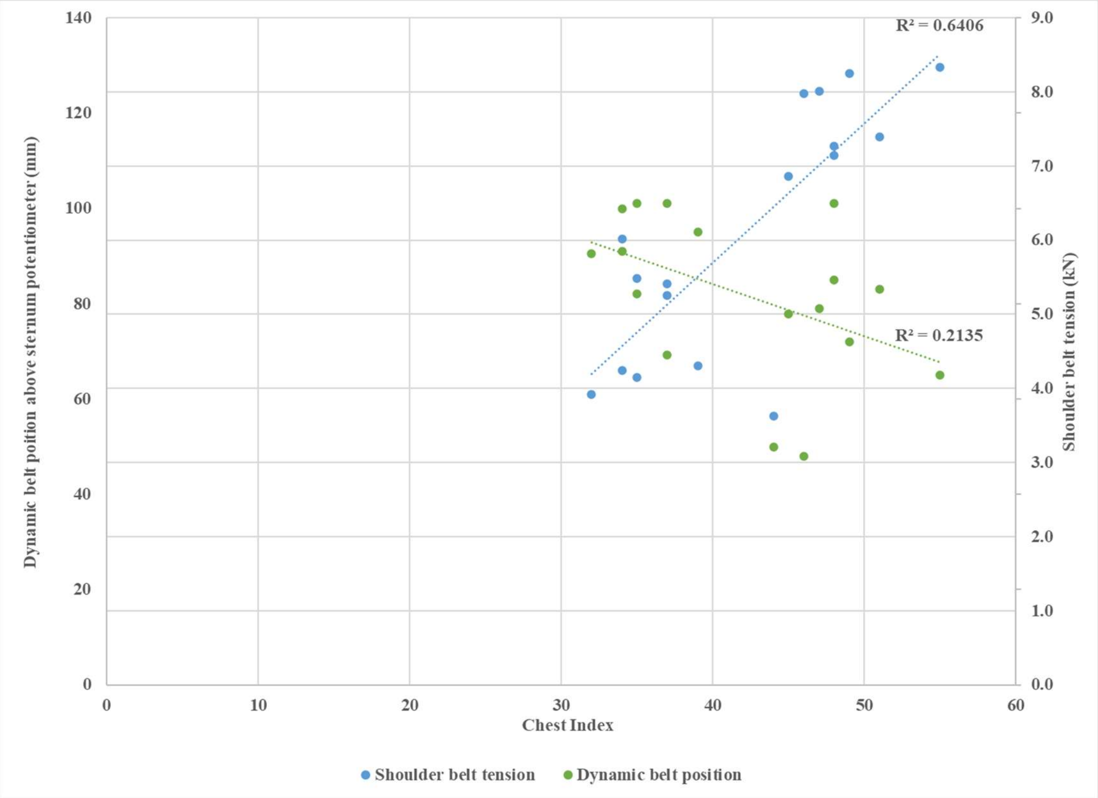

Figure 14. Correlation of Chest Index to belt position and shoulder belt tension

Abdominal Injury
The primary source of abdominal injuries is loading from the lap belt after it migrates over the ASIS and into the abdomen, called submarining. The H3-5F dummy does not have sensors to directly assess the risk of injury due to this type of loading to the abdomen, so the increased risk due to this belt behavior was assessed by observing whether the behavior is present. In this research series, submarining was evaluated primarily with video analysis of the belt position and confirmed with ASIS and lap-belt load cells. Figure 15 shows examples of stable belt position (Figure 15a), the lap belt migrating over only the right ASIS (15b), and the lap migrating over both the left and right ASIS (15c). Table A1 (Appendix) shows a summary of submarining behavior for all tests. Lap belt migration over one or both ASISs were both considered submarining. Submarining was observed in 6 of the 17 vehicles with standard belts and 6 of the 15 vehicles with pretensioners and load limiters. Overall, submarining was observed in 38% percent of the tests.

Figure 15a. Stable belt position

Figure 15b. Belt migration over the right ASIS

Figure 15c. Belt migration over both the left and right ASIS

Femur injury

To assess the risk of lower extremity injuries in the rear seat, this study looked at femur axial compression in the left and right femur. Results for femur compression are shown in Figure 16. The knees contacted the front seat in only 6 of the 32 vehicles, several of which had the smallest rear-occupant space: the CF21006 Yaris, CF21007 Sentra, CF21010 Rio, CF21011 Colorado, CEF2109 CX-5 and CEF2103 Encore. Contacts are shown in red in Figure 16. Femur compression values ranged from 0.1 to 1.3 kN, which are well below the IARV of 6.2 kN. The highest femur compression value reported was from a case where the knees contacted the front seatback.

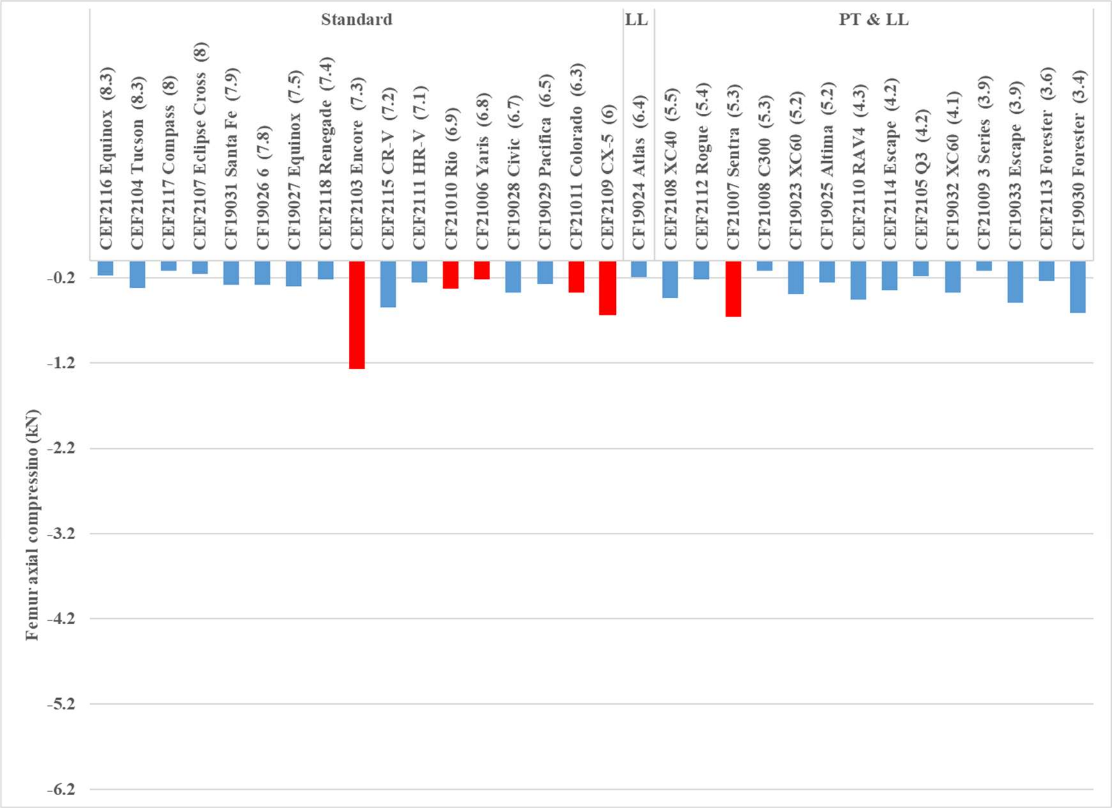

Figure 16. Peak femur axial compression values with contacts shown in red. Vehicle tests are organized by rear belt type (standard, load limiter only [LL], and pretensioner and load limiter [PT &LL]) and ordered by shoulder belt tension (kN).

DISCUSSION

Advancements in rear seat-belt technology are important countermeasures for improving safety for rear-seat occupants. However, the presence of force-limiting and pretensioning belts in these tests did not guarantee better overall performance.

Head Injury

The two primary sources for head injuries in the rear seat are impacts with the vehicle interior and inertial loading [7]. Injury metrics, HIC 15 and peak resultant head acceleration, are both meant to reflect injury due to contacts. In this dataset, both peak resultant head accelerations and HIC 15 showed elevated values for the one test where the rear-seat occupant's head impacted the seatback. HIC 15 values, however, also predicted risk of skull fracture as high as 40% for non-contacts, which are unlikely in the absence of hard contacts. HIC 15 had a strong relationship with belt tension (r = .85), which can relate to inertial injuries, but, according to Prasad and Mertz, neck forces and not HIC 15 should be used to assess restraint performance [21].

Since head contacts were rare, these two injury metrics alone do not provide a robust evaluation of how well the head is protected from injury in the rear seat. One potential trade off with the introduction of force limiting in the rear seat is increased head excursion. In this dataset, the head only contacted the front seatback in the vehicle with the smallest occupant space. The absence of head contacts for the rear occupant was unexpected, since head injuries comprise 9% of serious injuries for belted adults and teens and 30% of serious injuries for belted children in the rear seat, and over half of these injuries for children are with the front seatback [5, 6]. In three vehicles, the front seatback pivoting forward prevented a head contact. In an additional 13 vehicles, the head came within 50 mm of the pretest position of the front seatback. Changes in occupant stature, mass, or crash severity could influence head-impact results for real-world occupants, so it is important to encourage automakers to design restraints that maintain a larger buffer of space between the occupant's head and the front seatback than is required for the H3-5F in this test condition.

Neck Injury

Parenteau and Viano did not observe any AIS 3+ neck injuries in their 2003 study of NASS-CDS belted rear-seat occupants in frontal crashes [5]. Jermakian et al. found the same results for cases in the NASS-CDS dataset in their 2019 study but found very serious neck injuries in the FARS cases [7]. In the FARS cases, neck injuries were documented as atlantooccipital dislocation/disarticulation, cervical spine fractures and "massive neck trauma" or "neck instability." Some of these cases reported no head contacts, but serious thorax injuries from belt loading, indicating that these neck injuries may be due to high inertial loads. Upper neck tension in the current dataset had a positive correlation with shoulder belt tension (r = .76), indicating that technology that limits belt forces can also reduce forces in the neck. Though there is an absence of neck injuries in the NASS-CDS dataset, it is important to set thresholds for performance to pragmatic values that will encourage safety technology that limits the neck tensions that lead to very serious neck injuries in higher severity crashes.

Maximum Nij values are dominated by neck tension values; however, as shown in Figure 7, there are loading scenarios like head contact with the front seatback where neck tension alone does not capture how these forces affect the neck. In these cases, Nij reflects the elevated extension moments.

Neck compression values for the rear-seat occupants were well below IARVs, however, innovative restraints in the rear seat may change patterns in occupant loading, so monitoring compression values remains important.

Chest Injury

Several researchers have documented the thorax as the most frequently injured body region for belted adults in the rear seat, yet Kuppa et al. observed that dummy head and neck injury metrics predict a higher risk of injury in the rear seat [5, 7, 9]. Similar results were observed in the current study where HIC 15 and upper neck tension exceeded the IARV in 25% and 44% of the vehicles, respectively, but sternum deflection only exceeded the IARV in 9% of the vehicles. In these tests, shoulder belt tension explained only 19% (r = .44) of the variance in sternum deflection values, despite previous research suggesting that shoulder belt tension should explain nearly all of the variance in this outcome in a consistent vehicle environment (98%; r = .99) [13]. Reducing shoulder belt tension with force-limiting technology is a primary strategy for reducing chest injuries, but these results showed that sternum deflection did not reflect the benefit of this technology [22, 23].

In this dataset, belt positions varied as much as 82 mm of vertical distance on the centerline of the thorax due to belt-anchorage location variability, belt technology, and dummy kinematics. Edwards et al., observed an inverse linear sensitivity between shoulder belt position relative to the sternum potentiometer and the sternum deflection measurement, which confirmed observations from other researchers that the H3-5F has a sensitivity to belt position [10-13]. However, this sensitivity does not have an established relationship with human sensitivity to belt position. Vehicle test results also show a relationship between the measured dynamic belt position and sternum deflection (r = .62), which obscures the benefit of added belt technology and provides a challenge for consumer information organizations in trying compare the effectiveness of restraint designs.

The sensitivity from Edwards et al. [13], the measured dynamic belt position, and sternum deflection were used to calculate the expected sternum deflection, called Chest Index, for a given vehicle and restraint system if the belt had been placed 17 mm above the sternum potentiometer. Results for Chest Index show an improvement over sternum deflection in reflecting the benefits of added belt technology. While pretensioner and load limiter belts and standard belts had similar ranges of values for sternum deflection, all Chest Index values for standard belts, with one exception, were higher than all the values for pretensioner and load limiter belts. In contrast with sternum deflection, Chest Index also shows little correlation with dynamic belt position (r = .14) and an improved relationship with shoulder belt tension (r=0.79) compared with sternum deflection (r = .62). These results indicate that the Chest Index value can differentiate between restraint designs without results being confounded by the dummy's sensitivity to belt position. However, caution must be used with applying this metric to prediction of human injury. Because it is a departure from the sensor output for which injury risk curves were developed, the values reported should not be used to predict thoracic injury risk.

Additionally, Edwards et al. established the sensitivity of sternum deflection to belt position for belt positions that ranged from 25 to 81 mm above the sternum potentiometer [13]. These values were chosen, on the low end, because it was the lowest position where the shoulder belt would stay on the shoulder during the event and, on the high end, because it was the highest position achievable without moving beyond the molded flesh at the dummy's neck. However, in some vehicles in the current dataset, belt positions were measured as high as 131 mm above the chest potentiometer. Photographic review determined that belt positions higher than 110 mm compromise the effectiveness of the restraint system because the shoulder belt is actually loading the neck (Figure 11) instead of the thorax. Further, since the belt is no longer loading the thorax in these positions, extrapolating the linear relationship found in Edwards et al. [13] beyond 110 mm is not appropriate.

Abdominal Injury

Abdominal injuries account for 5% and 10% of all AIS 3+ injuries for adults and children wearing seat belts in the rear seat, respectively [5,6]. Jermakian et al. observed that the majority of abdominal injuries were the result of lap belt load and saw evidence of submarining in three quarters of the abdominal injury cases [7]. Because the H3-5F lacks sensors to assess risk for abdominal injury, increased risk of abdominal injury can only be assessed by observing whether submarining behavior is present. Submarining behavior was observed in 38% of this test group, evenly distributed between vehicles with and without pretensioners and load limiters. Though it is unknown if this frequency represents the incidence of submarining in the field because submarining can occur in the absence of injury, it does indicate that the H3-5F positioned according to IIHS's rear-occupant seating procedure [14] can highlight issues with belt migration over the ASIS.

Pelvis/femur injury

Lower extremity injuries account for 8% of all AIS 3+ injuries for belted rear-seat adults [5]. The dummy's knees contacted the seatback in 6 of the 32 vehicles tested, but none of these impacts resulted in loads that indicate a high risk of injury. Though the H3-5F dummy represents the stature of the majority of rear-seat occupants, its stature may be a shortcoming when trying to represent risk of femur injuries. Further, though the H3-5F does reflect the risk of submarining, the occupant kinematics after the lap belt leaves the pelvis may not be biofidelic, and real-world occupants may move further forward than the dummy, putting the femur at risk of fracture. Though current injury values do not indicate a significant risk of injury, it is important to monitor femur axial force because it is a potential load path for occupant restraint.

CONCLUSION

Dummy head injury metrics, HIC 15, and head resultant acceleration reflected the risk of head injury due to impacts with the vehicle interior. However, these tests did not show the field-relevant problem of head contacts with the vehicle interior, which necessitates an excursion evaluation that rewards leaving a large buffer of space between the occupant's head and the seatback to account for occupants of larger stature. Dummy neck tension correlated with shoulder belt tension, indicating that neck tension reflects the high inertial loads that can cause fatal inertial head-neck junction injuries. Nij reflects the elevated moments associated with head impacts. Sternum deflection underestimated the frequency of chest injury observed in field data relative to neck injuries, in part due to variance in belt position. Adjusting the sternum deflection to compensate for the belt position, called Chest Index, provided a metric that better reflected the expected benefit of force limiting and pretensioning. The H3-5F dummy showed a propensity for submarining, an important risk factor for abdominal injuries. Femur axial forces for the H3-5F, however, showed no indication of injury. The alignment of crash test results with real-world outcomes is affected by using one stature of ATD (H3-5F) to represent the broad range of occupants in the rear seat and by the limitations of the H3-5F dummy. Adding head excursion limits to prevent head impacts, compensating for the effect of belt position on chest deflection and setting neck-tension performance boundaries to encourage safety technology that reduces neck tensions all help address the known ATD shortcomings in order to develop reliable assessment metrics. However, other shortcomings in representing field injuries, like lower extremity injuries, may not be assessed in a way that will affect design changes but will only ensure that countermeasures do not increase values to injurious levels.

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APPENDIX

Table A1.
Occupant injury metrics and test metrics

Belt technology	Test ID	Shoulder belt tension	HIC 15	Peak acc	Head contact	Upper neck Tension	Upper neck Compression	Maximum Nij	Nij mode	Chest deflection	Dynamic belt position (maximum)	Dynamic belt position at max chest	Chest Index	Left femur	Right femur	Submarining	Cross excursion line
IARV			**779**			**2.6**	**2.5**	**1.00**		**-41**				**-6.2**	**-6.2**		
Units		**kN**		**g**		**kN**	**kN**			**mm**	**mm**	**mm**		**kN**	**kN**		
Standard	**CEF2116**	8.3	1393	105	No	4.3	0.5	1.30	NTF	-42	65	65	55	-0.2	-0.2	No	0
	CEF2104	8.3	947	92	No	3.0	0.4	1.09	NTF	-35	74	72	49	-0.3	-0.2	No	1
	CEF2117	8	827	83	No	3.5	0.1	1.14	NTF	-33	100	79	47	-0.1	-0.1	No	0
	CEF2107	8	1124	98	No	3.3	0.0	1.04	NTE	-39	48	48	46	-0.1	-0.1	No	2
	CF19031	7.9	853	88	No	3.3	0.7	1.07	NTE	-31				-0.3	-0.1	No	1
	CF19026	7.8	951	91	No	3.4	0.7	1.11	NTF	-31				-0.3	-0.1	Yes	1
	CF19027	7.5	945	94	No	3.7	0.1	1.10	NTF	-42				-0.3	-0.2	Yes	0
	CEF2118	7.4	760	82	No	3.4	0.6	1.12	NTF	-34	107	83	51	-0.2	-0.1	No	0
	CEF2103	7.3	687	77	No	2.5	1.1	0.84	NTF	-32	85	85	48	-0.4	-1.3	No	2
	CEF2115	7.2	541	70	No	2.8	0.1	0.81	NTF	-23	130	130	-	-0.5	-0.5	No	0
	CEF2111	7.1	750	85	No	3.7	0.5	1.14	NTF	-28	101	101	48	-0.3	-0.2	Yes	0
	CF21010	6.9	433	74	No	3.1	0.0	0.92	NTF	-31	78	78	45	-0.3	-0.1	Yes	1
	CF21006	6.8	589	74	No	2.9	1.7	1.05	NTF	-32				-0.2	-0.2	No	2
	CF19028	6.7	512	71	No	2.5	0.0	0.79	NTF	-43				-0.3	-0.4	Yes	0
	CF19029	6.5	451	66	No	2.0	0.1	0.70	NTF	-28				-0.2	-0.3	No	0
	CF21011	6.3	802	106	Yes	1.6	1.3	0.88	NTE	-34				-0.3	-0.4	No	2
	CEF2109	6	750	88	No	3.7	0.3	1.12	NTF	-20	123	100	34	-0.6	-0.4	Yes	0
LL	**CF19024**	6.4	598	73	No	2.4	0.1	0.66	NTF	-40				-0.1	-0.2	No	1

Belt technology	Test ID	Shoulder belt tension	HIC 15	Peak acceleration	Head contact	Upper neck Tension	Upper neck compression	Maximum Nij	Nij mode	Chest deflection	Dynamic belt position (maximum)	Dynamic belt position at max chest	Chest Index	Left femur	Right femur	Submarining	Cross excursion line
PT & LL	CEF2108	5.5	309	55	No	1.8	0.4	0.52	NTF	-23	82	82	35	-0.3	-0.4	No	0
	CEF2112	5.4	581	75	No	2.4	0.0	0.66	NTF	-21	110	101	37	-0.2	-0.1	Yes	1
	CF21007	5.3	465	71	No	3.2	1.2	0.93	NTF	-21				-0.7	-0.3	Yes	0
	CF21008	5.3	482	68	No	2.3	1.4	0.92	NTE	-27	69	69	37	-0.1	0.0	No	1
	CF19023	5.2	234	49	No	1.6	0.3	0.50	NTF	-26				-0.4	NA	No	0
	CF19025	5.2	445	69	No	2.3	0.1	0.67	NTF	-32				-0.2	-0.3	Yes	0
	CEF2110	4.3	396	62	No	2.0	0.1	0.61	NTF	-24	95	95	39	-0.5	-0.3	Yes	0
	CEF2114	4.2	251	51	No	1.7	0.6	0.53	NTF	-21	92	91	34	-0.3	-0.1	Yes	1
	CEF2105	4.2	468	71	No	2.4	0.2	0.63	NTF	-20	101	101	35	-0.1	-0.2	Yes	1
	CF19032	4.1	250	51	No	1.7	0.1	0.48	NTF	-25				-0.3	-0.4	No	1
	CF21009	3.9	224	51	No	2.1	0.1	0.60	NTE	-20	91	91	32	-0.1	-0.1	No	1
	CF19033	3.9	222	49	No	1.6	0.5	0.53	NTE	-27				-0.5	-0.2	No	0
	CEF2113	3.6	251	55	No	1.9	0.1	0.75	NTE	-37	50	50	44	-0.2	-0.2	No	1
	CF19030	3.4	232	53	No	1.7	0.5	0.95	NTE	-41				-0.6	-0.1	No	1

Table A2.

Correlation coefficients and coefficients of determination for select metrics

	R^2		**r**	
	Shoulder belt tension	**Shoulder belt position**	**Shoulder belt tension**	**Shoulder belt position**
HIC15	0.73	NA	0.85	NA
Peak acc	0.66	NA	0.81	NA
Neck tension	0.58	NA	0.76	NA
Neck compression	0.01	NA	0.10	NA
Maximum Nij	0.54	NA	0.74	NA
Chest deflection (32 tests)	0.19	NA	0.44	NA
Chest deflection (18 tests)	0.39	0.57	0.62	0.75
Chest Index	0.64	0.21	0.80	0.46
Shoulder belt tension	NA	0.02	NA	0.13