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BLAST MITIGATION SEAT ANALYSIS – DROP TOWER DATA REVIEW

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ABSTRACT

A comprehensive analysis of data collected during an evaluation of blast energy-attenuation (EA) seats was conducted to review the performance of commercially available and prototype seat assets. This evaluation included twelve models of seats tested at two separate drop severities with three sizes of anthropomorphic test devices (ATDs) to develop test methodologies and assess the appropriateness of using injury assessment reference values (IARVs) for all occupant sizes.

INTRODUCTION

Blast energy-attenuation (EA) seats, although not new to the market, have not been fully characterized with respect to energy attenuation capability and the resulting effects on occupant protection. The U.S. Army – Tank Automotive Research, Development and Engineering Center (TARDEC) Ground Systems Survivability (GSS) Interiors Seat Team tested and evaluated EA seats over a one-year period using a drop tower test method. Data from three different anthropomorphic test devices (ATDs, or crash test dummies) was recorded on tests in twelve different seat styles that were dropped at two different heights on the drop tower. The ATDs represented 90 percent of the human population and are characterized as a 5th percentile female, 50th percentile male, and 95th percentile male. The data was checked for quality and anomalies, and a method was developed to display all of the data in an easily referenced and understood format. This data was compared to the Army Research Lab / Survivability / Lethality / Analysis Directorate (ARL/SLAD)[1] crew injury criteria for accelerative events and the enhanced injury assessment reference values (e-IARVs) for the 5th percentile female, 50th percentile male, and 95th percentile male determined from existing biomedical literature by the Occupant Centric Platform (OCP) Technology Enabled Capability Demonstration (TECD) program's Enhanced Injury Assessment Reference Value Working Group[2] as a pass/fail threshold.

An evaluation of the data allowed the assessment of commercially available and prototype seats to understand the performance of the seats with varying occupant weights and to evaluate the test methodology and occupant injury assessment performance criteria. The results from this data review afforded a better understanding of how seat design affects performance with varying occupant size, including weight and stature. The analysis also provided the TARDEC Seat Team with an overview of general trends and lessons learned.

METHODOLOGY

In efforts to gain an understanding of the current blast EA seats, assets from various vendors, including commercially available and prototype seats with a variety of EA mechanisms, were purchased for evaluation on the drop tower located at the TARDEC Occupant Protection

Laboratory (OP Lab). A matrix was developed to assess the seats with a simulated blast input with test variables including two severities (200 g or 350 g peak acceleration pulse), three ATDs (Hybrid III 5th percentile female, 50th percentile male, or 95th percentile male), and with or without personal protective equipment (PPE). The seats were tested in their recommended use range. Several of the seats were designed specifically for the lower input velocities. Efforts were made in the matrix development to maximize information gained with a limited number of seat assets. A total of twelve seat models were tested in the combinations shown in Figure 1.

	200 g						350 g						
	5th		50th		95th		5th		50th		95th		
	PPE	No PPE	PPE	No PPE	PPE	No PPE	PPE	No PPE	PPE	No PPE	PPE	No PPE	
	1	2	3	4	5	6	7	8	9	10	11	12	Total
A	1	1	1		2		1	1	1		1		9
B	2		4		2								8
C							2	2	2		2		8
D	2	2	2		1		2	2	2		2		15
E	1		1		1		1		1				5
F		4	2	2				2	6		2		18
G	2	2					2	2					8
H	2	2	2		2								8
I	2	2	2		2								8
J	2	2	2		2			1					9
K	1	1	3	1	1	1							8
L							6		1		1	1	9
Total	15	16	19	3	13	1	14	10	13	0	8	1	113

Figure 1. Test matrix.

Drop Tower Setup

Testing blast mitigation seats on a drop tower has been established as a preliminary evaluation of seat assets without introducing the variability or cost associated with a full-scale blast test. All drop tower testing of the data included in this report was conducted on the rig shown in Figure 2. The testing was performed between July 2012 and July 2013, and temperature and humidity data was recorded for each test event. Each test asset was affixed to the drop tower platform, which was then lifted to a designated height based on desired pulse severity, and released in free-flight to impart a simulated blast load to the seat system. The platform was constrained to vertical motion, with the highest drop height set at 4.5 m (177”). An additional 680 kg (1,500 lbs) of payload was allowable beyond the base weight of the platform, which is currently 454 kg (1,000 lbs). The pulse profile, including maximum acceleration, time to peak, and delta velocity, could be tuned by drop height, platform payload, and energy absorbing material placed between the platform and seismic mass base. For each test, the motion of the platform was recorded by primary and secondary accelerometers.

For this evaluation, the drop tower was released from approximately 1.2 m (48”) or 4.0 m (156”) to achieve peak accelerations of 200 g or 350 g, respectively, with pulse durations of approximately 6 ms. These pulses resulted in delta velocities of approximately 5 m/s and 8 m/s, respectively, when calculated by integrating the accelerometer data.

Figure 2. Drop tower fixture.

ATD Setup

Each test included an instrumented and ballasted ATD to measure forces, moments, and accelerations imparted to the occupant. Three sizes of ATDs were used in this evaluation to cover 90% of the human population size, namely a 5th percentile female (base weight of 108 lbs), 50th percentile male (base weight of 171 lbs), and 95th percentile male (base weight of 223 lbs). The ATDs were tested in a “no PPE configuration”, which consisted only of the Army Combat Uniform (ACU) and boots, or in a “PPE configuration” which comprised the ACU, Advanced Combat Helmet (ACH), boots, and an Improved Outer Tactical Vest (IOTV) in the Squad Automatic Weapon (SAW) gunner configuration. The addition of PPE increased the base weight of each ATD by approximately 60 lbs (Figure 3).

Figure 3. ATD with no PPE (left) and fully encumbered (right).

The fleet of ATDs all contained the same instrumentation, which included accelerometers in the head, thorax, and pelvis as listed in Table 1. Load cells to measure forces and moments were located in the upper neck, lumbar spine, femur, upper tibia, and lower tibia. The data recorded off of each transducer was compared to the ARL/SLAD crew injury criteria for accelerative events for the 50th percentile male. The OCP TECD e-IARVs Working Group determined criteria for the 5th percentile female, 50th percentile male, and 95th percentile male from existing biomedical literature. The working group included subject matter experts (SMEs) within TARDEC, ARL/SLAD, U.S. Army Aeromedical Research Laboratory (USAARL), other Department of Defense (DoD) organizations, and industry SMEs who helped to develop the current Federal Motor Vehicle Safety/U.S. Department of Transportation injury criteria.

Table 1. ATD instrumentation channel list.

Location	Channels
Head	Ax, Ay, Az
Upper Neck	Fx, Fy, Fz, Mx, My, Mz
Thorax	Ax, Ay, Az, Dx (displacement)
Lumbar Spine	Fx, Fy, Fz, Mx, My, Mz
Pelvis	Ax, Ay, Az
Femur	Fx, Fy, Fz, Mx, My, Mz (per leg)
Upper Tibia	Fx, Fy, Fz, Mx, My, Mz (per leg)
Lower Tibia	Fx, Fy, Fz, Mx, My, Mz (per leg)

Prior to each test, the ATD, either equipped with the ACU and boots only or with PPE, was placed in the seat and positioned following internal guidelines. The locations of the H-point, head, knees, and ankles were recorded with a FARO arm for reference relative to the seat for some of the testing. Additional injury assessment reference values such as head injury criterion (HIC) and dynamic response index (DRI) were calculated when applicable.

RESULTS

The primary focus of the testing was to evaluate the test methodology developed for blast mitigation seat analysis via drop tower, namely, the ability of commercially available or prototype seats to produce occupant injury values below the internal OCP thresholds for all body segments for all size occupants. Each ATD channel was reviewed to determine if the maximum or minimum value exceeded the associated IARV limit. Bar charts displaying the peak values for all data channels were created as a concise reference to determine if IARV limits were exceeded for any test configuration. Dwell curves were produced for any channel if required by the associated IARV, as dwell curves contained additional information regarding the length of time that any load was sustained, which could be more informative than peak value. This time history data could flag issues in the dwell curves that would not appear in maximum and minimum peak analyses.

An example of the data analysis for normalized lumbar compression peak values of all 113 tests is shown in Figure 4. A review of the data showed compliance with the OCP IARV limits for some of the seats in the tested configurations, leading to the conclusion that the target loads and accelerations set by OCP were attainable and appropriate. Figure 5 shows the data from Seat ‘K’, which demonstrated compliance with the OCP and ARL/SLAD injury assessment reference values when tested with all three ATDs at 200 g.

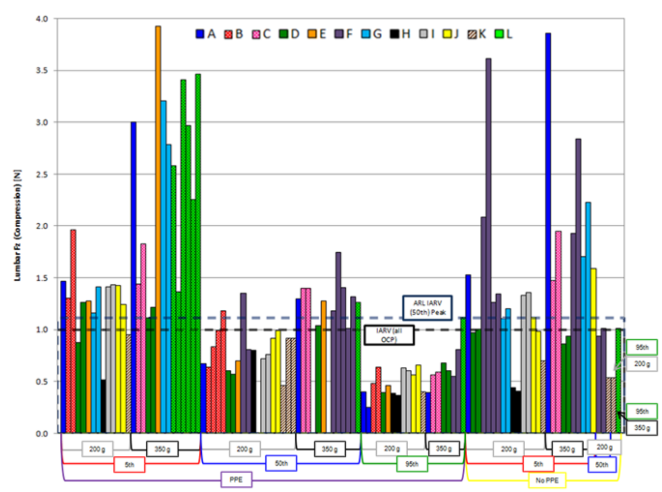

Figure 4. All test data normalized lumbar Fz compression data compared to OCP IARV limit (black dashed line) with slightly higher ARL/SLAD peak limit for 50th percentile male (blue dashed line).

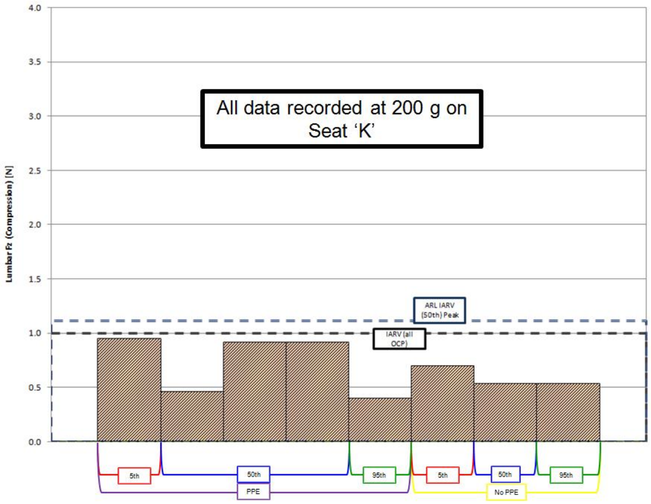

Figure 5. Data review of Seat 'K' demonstrates that compliance with the OCP IARV limits are attainable with respect to lumbar compression (normalized data shown).

The primary goal of the data analysis effort was to produce a succinct visual summary of all test results in an efficient manner to evaluate the test methodology and resulting injury values of the ATDs in the varying seats. Bar charts like those shown in Figure 4 and Figure 5 were produced for all ATD channels for quick reference. A thorough quality check of the data was performed to determine if all data was valid and to explain any anomalies within the data set. Review of videos, pre- and post-test photographs, and discussions with the test engineers on site provided insight into any discrepancy in the data or anomalies in seat performance. As some of the seats were prototypes, there were issues noted with energy absorption mechanism malfunctions and deformation to seats due to testing, as many of the seats were reused after appropriate reset activities were completed. Most of the tested seats required a specific EA mechanism based on occupant weight or impulse loading, multiple EA device changes (e.g. after two drops), or the seat was designed specifically for a specific impulse, which makes direct comparisons between seat performance more difficult.

Some of the recorded data from the platform was questionable due to various issues with the accelerometers over the full series of 113 tests. Some examples of these issues with the platform accelerometers included mounting problems due to rough or imprecise mounting surfaces and cable tie down issues resulting in damaged or severed cables or cable "whip". The original platform was subject to structural deformation, causing the accelerometers to occasionally record local structure deformation instead of global platform motion. Furthermore, at times, the accelerometers experienced issues with excitation, causing them to overshoot or undershoot the actual acceleration, and sampling bandwidth issues were also reported periodically by testing personnel. Although the data from the accelerometers could not be used in every test, drop height information could be used to characterize the acceleration and impact velocity of each drop at the known drop heights from testing with successful data recording. Additionally, the rebound of the platform at impact created a delta velocity that was slightly higher than the impact velocity, which was not measured at the time of this testing. The rebound was a result of the rubber used as energy absorption material and the condition of the seismic mass located underneath the platform.

Due to limitations in the current HVAC system in the OP Laboratory facility, indoor temperature was affected by outdoor weather conditions. The ATD instrumentation was used outside of the recommended temperature range, and this could have introduced some variability in test results, but for the purposes of this analysis, the authors are assuming the impact to the data was negligible. The data variability could not be quantified at this time.

Throughout the test series and accompanying data analysis, several lessons were learned and are explained in the following text. Although all ATD data channels were reviewed for IARV exceedances, an analysis of the ATD trends allowed for the formation of general observations of "go/no-go" channels to review if time is limited (Figure 6). Lumbar compression (-Fz) seems to be the go/no-go injury criteria when evaluating the seat as a survival system. The chart in Figure 7 depicts a passing or failing IARV for all tests on a particular seat with green or red, respectively, for the 5th percentile female during 350 g tests. Lumbar compression is red or yellow (meaning at least one test passed but the other tests failed with respect to IARV) for all 5th percentile female tests at 350g, demonstrating that the most sensitive response of the ATD to seat performance was lumbar compression (and dynamic response index (DRIz), which was calculated based on pelvis acceleration). The direct load path from the platform, or during an underbody blast, is through the floor, into the seat, and directly into the pelvis and lower spine. The energy through the spinal column is absorbed as it travels upward, making upper neck compression (-Fz) less important to monitor, except in the 5th percentile female. Additionally, lumbar shear (±Fx), due to fore-aft shifting in the seat, and chest resultant acceleration, due to global motion, were more likely to exceed IARV levels due to seat design.

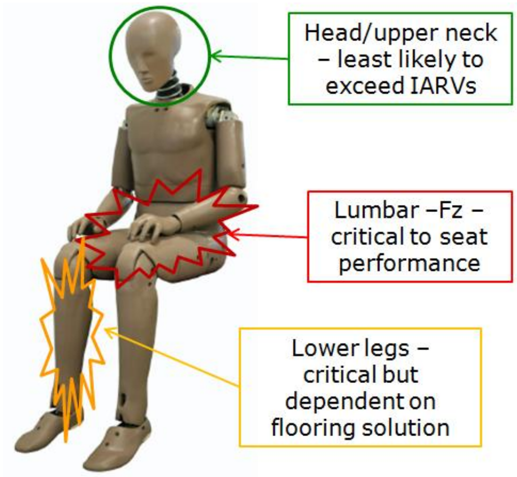

Figure 6. Schematic of ATD with body segments marked in order of importance.

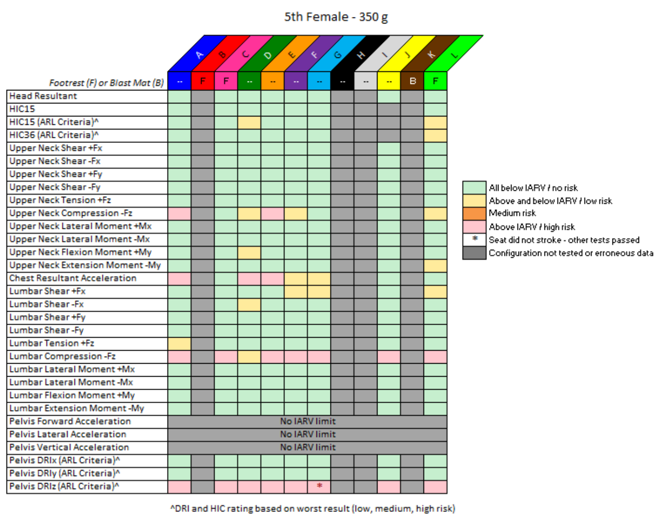

Figure 7. Pass/fail chart for 5th percentile female at 350 g demonstrates that lumbar compression (and DRIz calculated from the pelvis z-axis accelerometer) was the most sensitive factor with respect to the upper body.

A review of lower extremity injury values led to the conclusion that some type of flooring system should be included to mitigate lower leg injuries during a blast event. Although intuitive, the need for a flooring solution was confirmed by comparing lower and upper tibia IARVs between seats that featured foot rests or blast mats relative to those without. The pass/fail color charts in Figure 8 and Figure 9 demonstrate that those seats with flooring solutions were less likely to result in lower extremity issues, especially upper and lower tibia compression. Columns B, C, L, and K represented seats featuring blast mats or footrests, and these seats have the most "green" passes for lower extremities. Several ATD channels were dependent on the presence of a flooring solution, including femur shear (+Fx), femur tension (+Fz), femur moment (+My), and compression and moments about the upper and lower tibias (-Fz, ±Mx, ±My). The interaction of the feet with the floor propagated the load quickly through the ATD, leading to exceeding several injury criteria limits through the load path once the lower tibia loads were above the IARV limit. Additionally, the IARV limit for the lumbar in tension (+Fz) prior to the compression load could become problematic due to the transmission of loads through the lower leg, to the femur, and into the pelvis.

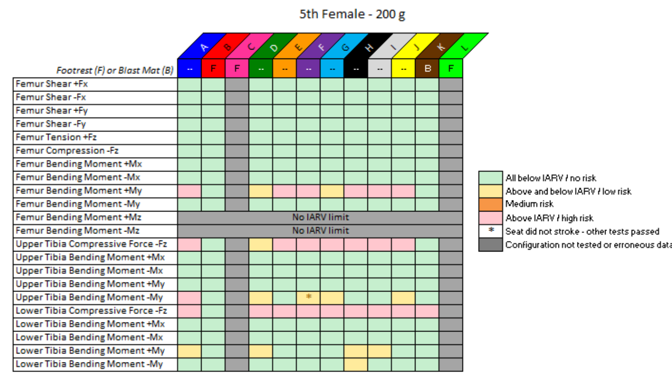

Figure 8. Pass/fail lower body chart for 5th percentile female at 200 g demonstrates that lower extremity injuries are less likely with a flooring solution (Seats B and K feature blast mats or footrests).

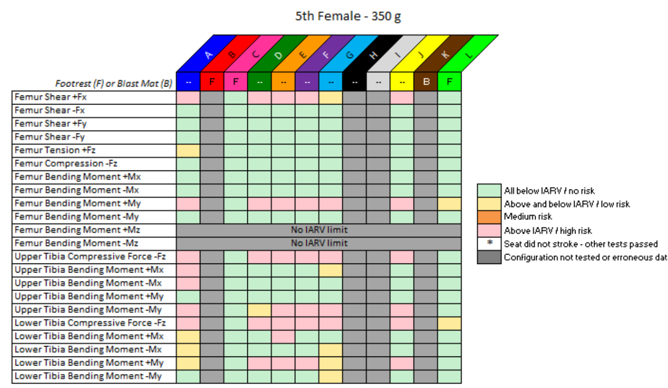

Figure 9. Pass/fail lower body chart for 5th percentile female at 350 g demonstrates that lower extremity injuries are less likely with a flooring solution (Seats C and L feature blast mats or footrests).

Additionally, one of the seats did not stroke properly on a few of the tests, so a direct comparison between lumbar compression and tibia compression on the same seat model with and without stroke could be performed. This analysis showed that lumbar compression decreased when the seat stroked properly (Figure 10), as expected, and tibia loads were consistent between the stroking and non-stroking seat, as the seat design had little to no effect on tibia injuries (Figure 11).

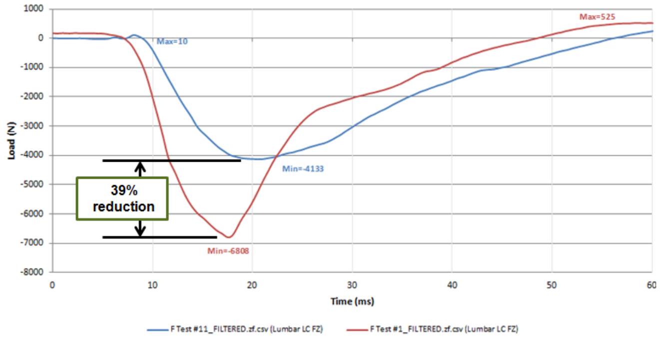

Figure 10. Decrease in lumbar compression between successive tests in non-stroking and stroking seats demonstrated the improvement in lumbar loading based on the energy absorption properties of the seat.

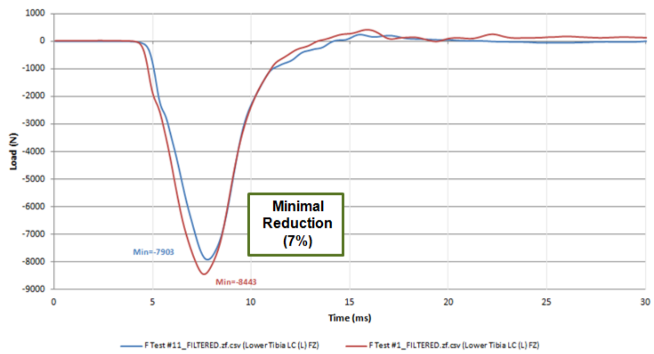

Figure 11. Minimal change in tibia forces between successive tests in non-stroking and stroking seats demonstrated lack of seat-dependence for lower extremity injuries.

Head accelerations and upper neck loads and moments are considered lower priority in drop tower analysis. Although the HIC is included on the OCP IARV measurement list, HIC is only relevant when head contact with a hard surface occurs, which is not common in drop tower testing unless a roof structure is installed over the seat. The 5th percentile female was most sensitive to upper neck loads and head acceleration, but Figure 7 (previously shown) displays very few exceedences for the head and neck.

Seat manufacturers currently design their systems for optimization during a blast event with an occupant representative of a 50th percentile male, and many seats were tuned for a 5 m/s event, or approximately a 200 g peak acceleration. Consequently, the majority of the seats passed the lumbar compression load for the 50th percentile male at this test condition as shown in Figure 12. The seats were less likely to produce occupant loads below the IARV for lumbar compression when the drop height was increased. A review of the lumbar compression data for the 95th percentile male demonstrates that the additional weight of the occupant and higher IARV thresholds leads to passing numbers for almost all seat models (Figure 13). None of the seats bottomed out under the increased weight, which could result in an increase in lumbar loads. As expected, the seats were not designed for the lightest occupant, leading to lumbar compression limits over the threshold of the 5th percentile female for 83% of the seats tested (Figure 14). The lighter occupant may prevent the seat from fully stroking, and the 5th percentile female's IARV limit for lumbar compression is substantially lower than the larger occupants, at approximately 40% of that of the 95th percentile male. Lumbar loads above the IARV limit for the 5th percentile female reached values up to 400% of the limit, while the highest lumbar compression load for the 95th percentile male was approximately 110% of the associated IARV.

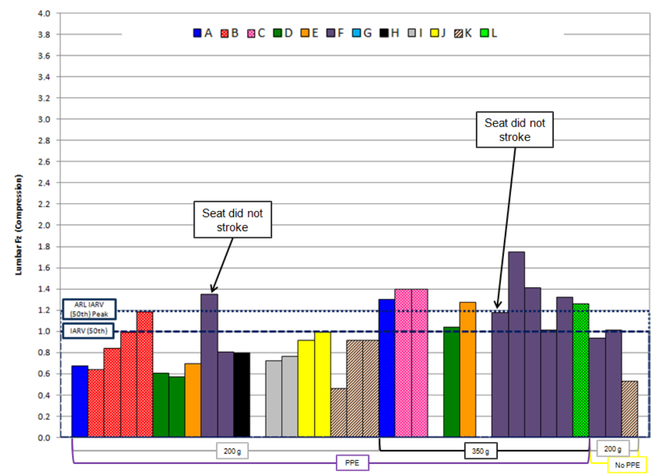

Figure 12. Normalized 50th percentile male lumbar Fz compression data compared to ARL/SLAD and OCP IARV limits (blue dashed lines).

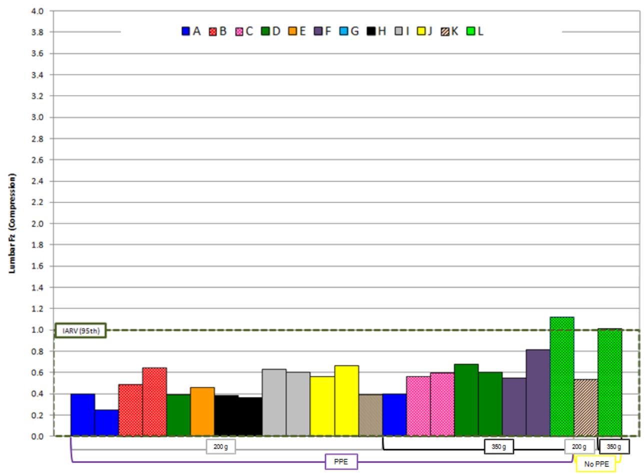

Figure 13. Normalized 95th percentile male lumbar Fz compression data compared to IARV limit (green dashed line).

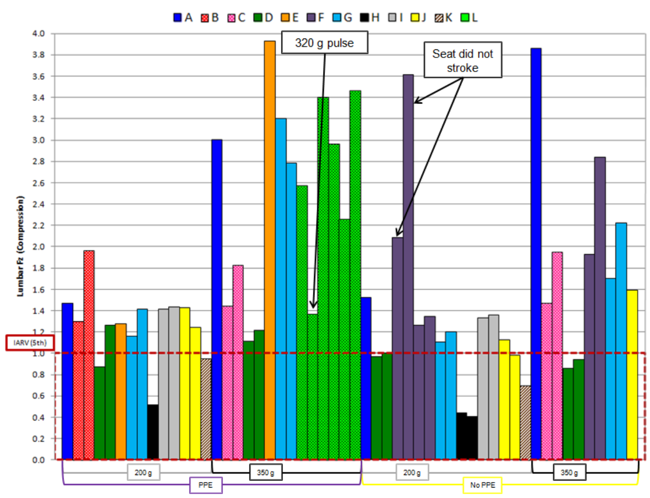

Figure 14. Normalized 5th percentile female lumbar Fz compression data compared to IARV limit (red dashed line).

The purpose of testing with and without PPE was to determine if the additional weight, in the case of the 95th percentile male, would cause a seat to "bottom out", or if the lack of weight, as in the unencumbered 5th percentile female, was too light to cause the seat to stroke as designed. However, due to the limited data sets, it was difficult to complete comparative analyses between ATDs with and without PPE. Figure 15 features matched pair testing for the 5th percentile female lumbar compression with and without PPE in the same seats at 200 g. The data collected in this evaluation seems to suggest that encumbrance level does not seem to have a major effect on injury values, but additional controlled testing would be needed to isolate the effects of PPE.

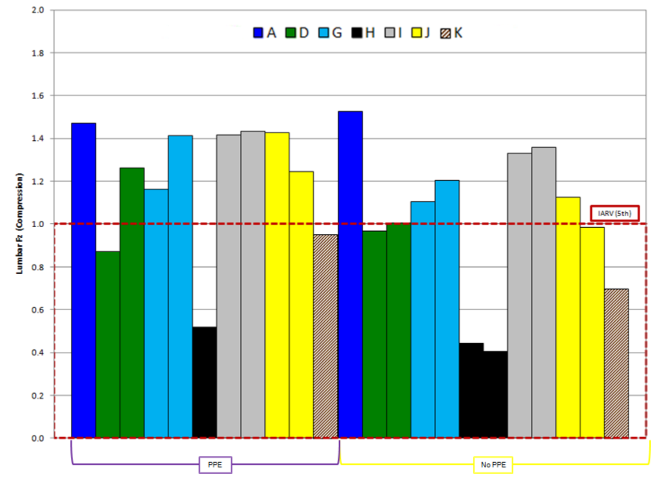

Figure 15. 5th percentile female normalized lumbar compression data at 200 g shows similar performance with and without PPE.

CONCLUSIONS AND FUTURE WORK

The drop tower testing and evaluation performed on commercial off-the-shelf (COTS) and developmental seats provided the TARDEC Seat Team with an objective assessment of the seats' performance with respect to the injury criteria. The test methodology and OCP IARV assessment criteria were evaluated and deemed acceptable for future use. Data analysis was performed for a quality check of the data and was used to determine general trends in ATD performance.

Complications with test setups lead to a list of caveats for this data analysis, including the loss of some of the platform accelerometer data and the effects of temperature on the ATD and its instrumentation.

Normalized lumbar compression data was presented for all three ATDs in all test configurations. ATD lumbar compression response seems to be the go/no-go injury criteria for seat performance assessment, and most seats seem to be designed to accommodate a heavier occupant for blast protection. The data review also determined that a flooring solution is directly responsible for the reduction in lower extremity injuries. Although PPE did not appear to greatly affect ATD response, additional studies would be needed for a concrete conclusion.

Caution should be used in directly comparing test results between seats based on differences in test setup, energy absorption devices, and the suitability of each seat based on occupant size and impulse. Although much useful information can be gleaned from this seat evaluation, several caveats in the data collected prevent this study from being used to select seats for a vehicle platform strictly based on their drop tower performance. Additionally, the authors suggest that testing to evaluate seating systems at standardized load profiles is conducted to determine which seats are viable options based on A-to-B comparisons, followed by additional testing with vehicle-specific impulses to prove out the seat design for a particular vehicle.

This evaluation was a preliminary effort to characterize EA seats via a drop tower, understanding that a drop tower test does not perfectly match the kinematics experienced during an actual blast event. This and future drop tower data should be compared to live fire data to identify and quantify similarities and differences in ATD and seat response. Further analysis of this data with respect to seat construction may allow an evaluation of seat characteristics to create an optimum seat design for ground vehicles. Additionally, this information may be used to aid in the development and selection of flooring solutions to mitigate lower extremity injuries.

A further evaluation of the OCP criteria may be needed to verify that the 5th percentile female and 95th percentile male IARVs were appropriate. This analysis would ensure that target IARVs were not set artificially high or low, causing seats to register as passes or failures unfairly.

The lessons learned from this initial evaluation and data analysis may be used to improve lab procedures and best practices. At this time, the drop tower is being relocated to another building on top of a new seismic mass which is expected to improve repeatability of the platform accelerations. The authors also recommend the implementation of a reliable speed trap that measures impact speed at the T-zero event to verify alignment between platform accelerometers, measured impact speed, and calculated delta-velocity.

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