USAARL-TECH-FR--2023-20

UNITED STATES ARMY AEROMEDICAL RESEARCH LABORATORY

Predicting Head Flail Response to Impact Acceleration using Historical Human Volunteer Data and a Velocity-based Linear Regression Approach

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Human subject data from legacy studies conducted at the Naval Biodynamics Laboratory (NBDL) were used in this report. The participation of the human subjects (1974 – 1995) was in accordance with procedures specified in the Secretary of the Navy Instruction 3900.39 series and the Bureau of Medicine and Surgery Instruction 3900.6 series. These instructions are based upon free and informed voluntary consent and met or exceeded the provisions of national and international guidelines at the time of research.

IRB Determination and Number

This study, USAARL 2009-030-005, was conducted as a sub-protocol of USAARL 2009-030, approved by the U.S. Army Medical Research and Development Command Institutional Review Board on 22 February 2012 (#M-10099).

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* 27-03-2023	**2. REPORT TYPE** Final Report	**3. DATES COVERED** *(From - To)* October 2021 - September 2022

4. TITLE AND SUBTITLE

Predicting Head Flail Response to Impact Acceleration using Historical Human Volunteer Data and a Velocity-Based Linear Regression Approach

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

622148BZ7FPCG

6. AUTHOR(S)

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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Aeromedical Research Laboratory
P.O. Box 620577
Fort Rucker, AL 36362

8. PERFORMING ORGANIZATION REPORT NUMBER

USAARL-TECH-FR--2023-20

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Medical Research and Development Command
Military Operational Medicine Research Program
504 Scott Street
Fort Detrick, MD 21702-5012

10. SPONSOR/MONITOR'S ACRONYM(S)

USAMRDC MOMRP

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution Statement A. Approved for public release: Distribution is unlimited.

13. SUPPLEMENTARY NOTES

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14. ABSTRACT

Models used for predicting head flail response were developed using an existing collection of human research volunteer (HRV) test data from the Naval Biodynamics Laboratory collection within the Biodynamics Data Resource (BDR) of the US Army Aeromedical Research Laboratory. Verification and validation were completed for the response models for frontal, axial, and lateral impact directions. The response models were verified to accurately predict the HRV response used to develop the model. The response models were validated to accurately predict the anteroposterior (AP), lateral, and vertical displacements for BDR HRV tests with similar boundary conditions but different input parameters than those of the BDR HRV tests used to develop the response model. The response models were not shown to be valid for predicting subject responses to higher sled acceleration levels and velocity changes found in literature. The primary reason for this is the differences in initial and boundary conditions between the NBDL dataset and the datasets from literature.

15. SUBJECT TERMS

Occupant flail, head flail, model, regression, Biodynamics Data Resource, BDR

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Loraine St. Onge, PhD
UNCLAS	UNCLAS	UNCLAS	SAR	38	**19b. TELEPHONE NUMBER** *(Include area code)* 334-255-6906

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Summary

Models for predicting head flail response were developed using an existing collection of human research volunteer (HRV) test data from the Naval Biodynamics Laboratory (NBDL) collection within the Biodynamics Data Resource (BDR) of the U.S. Army Aeromedical Research Laboratory. Head flail response models predicted the head flail response (i.e., anteroposterior, lateral, and vertical displacements) for frontal, lateral, and axial impact directions. Verification and validation were completed for the response models for frontal, axial, and lateral impact directions. The response models were verified to accurately predict the HRV responses used to develop the models. The response models were validated to accurately predict the anteroposterior (AP), lateral, and vertical head flail displacements for BDR HRV tests with similar boundary conditions but different input parameters than those of the BDR HRV tests used to develop the response model. The response models were not validated for predicting subject responses to higher sled acceleration levels and velocity changes found in literature; the primary reasons for this were the differences in initial and boundary conditions between the NBDL dataset and the datasets from literature.

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Acknowledgements

This work was supported by the U.S. Army Medical Research and Development Command (USAMRDC) (formerly the U.S. Army Medical Research and Materiel Command [USMRMC]) through the Military Operational Medicine Research Program (MOMRP), project MOM 23700.

This research was supported in part by an appointment to the Postgraduate Research Participation Program at the U.S. Army Aeromedical Research Laboratory administered by the Oak Ridge Institute for Science and Education (ORISE) through an interagency agreement between the U.S. Department of Energy and the USAMRDC.

This work was only possible through legacy data collected and preserved due to the vision, dedication, and scientific efforts of the research staff and military sponsors, along with the contributions of the human volunteers, at the Naval Biodynamics Laboratory (NBDL). Their contributions to occupant protection for Service Members and civilians will continue for generations.

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Introduction

Injuries to the head and upper torso in aircraft crashes are frequently reported, with head injuries reported most frequently out of all body regions (Barth & Balcena, 2007; Mapes, 2008; Shanahan & Shanahan, 1989). Excess motion/flail was reported as the cause of many of the most common injuries, which resulted from the body region striking against the aircraft structure or internal objects (Labun, 2014). Head strikes due to flail are particularly important because the loss of awareness, or consciousness, can prevent evacuation post-crash (DeWeese et al., 2017). Furthermore, injuries resulting from flail during a crash are costly to the military and military families. Because preventing flail of the head and body is of utmost importance for occupant survival, the Aircraft Crash Survival Design Guide (ACSDG), which defines occupant flail envelopes, was published in 1989 to guide crashworthy aircraft design (Coltman et al., 1989).

Recently, the ACSDG flail envelopes for a torso-restrained occupant were re-evaluated using human research volunteer (HRV) test data (Olszko et al., 2021). The HRV test data used for this evaluation were from the historical Naval Biodynamics Laboratory (NBDL) collection, which is housed in the Biodynamics Data Resource (BDR) data repository at the U.S. Army Aeromedical Research Laboratory (USAARL) (Schmidt et al., 2009). In these tests, a whole-body acceleration was applied to the restrained, seated HRV to replicate impact in several directions, including frontal, axial, lateral, oblique, and off-axis (Appendix A); the head flail responses from the BDR HRV tests were used to create new head flail response envelopes for each of the five impact directions. Comparing these new response envelopes to the ACSDG flail envelopes showed that for a well-restrained occupant with the sitting height of a 50 percentile male aviator at a non-injurious exposure level, the anteroposterior (AP) ACSDG curve can be considered adequate to prevent flail injury; the new AP head flail envelope fell within the AP ACSDG curve. However, the lateral ACSDG curve may not be considered adequate; the new lateral HRV-based head flail envelope fell outside the ACSDG curve, indicating that occupants may flail further than the ACSDG curve predicts and potentially strike objects located just outside the lateral ACSDG flail envelope.

The previous work by Olszko et al. (2021) provided a useful baseline for representing the head flail response for non-injurious exposure levels, but the response at higher, potentially injurious exposure is still unknown. Thus, this paper aims to develop models of the head flail response to impact using HRV response data from the BDR. These models may predict the occupant head flail response for higher exposure levels and inform recommendations for aircraft, restraint systems, and personal protective equipment (PPE) design.

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Methods

Models for predicting head flail response were developed using an existing collection of HRV test data from the BDR (Schmidt et al., 2009). Verification and validation were completed for the response models for frontal, axial, and lateral impact directions.

Head Flail Response Data

Head flail response and exposure data were obtained from the BDR for 714 HRV tests spanning 6 impact directions: frontal (-X), lateral (+Y), axial (+Z), oblique (-X+Y), and off-axis (+Z-X10 and +Z-X30). For the frontal, axial, oblique, and off-axis impact directions, head flail response data were available from the side camera view that provides AP and vertical positions. For the lateral and oblique impact directions, data were available from the front camera view that provides lateral and vertical positions. While the BDR HRV dataset includes flail response data for multiple points on the head, the focus of this work was the top-of-head (vertex) point because its displacement forms the perimeter of the strike envelope. Thus, all head flail positions and displacements referenced in this report refer to the top of the head, unless stated otherwise. Also, the top-of-head initial position for all BDR HRV tests was aligned to the sitting height of a 50th percentile male aviator. No adjustments to this initial position were made for the analysis in this report.

The methods used to collect and process the head flail response data are described in detail by Olszko et al. (2021) and briefly described herein. Digitized high-speed film for each test was tracked. Both sled- and subject-mounted phototargets were tracked. Head point data representing the head region were also collected for one to five total frames. Phototarget size data were collected for the initial frame. The tracked phototarget data were aligned in time and trimmed to exclude the rebound phase of the flail response. Then, the relationship (angle and distance) between the head phototargets and head point data was applied to every other frame with phototarget data to calculate the location of the head region with respect to the phototargets for all frames. Then, the phototarget size data were used to develop a scaling factor based on the known physical size of the phototargets. The scaling factor was applied to the phototarget and calculated head point data to calculate the displacement in physical units (i.e., meters). The displacement data were then calculated with respect to the seat origin and made representative of a 50th percentile male aviator (sitting height of approximately 93 centimeters [cm]). The seat origin was defined as the point at which the seat pan and seat back intersected the vertical midline of the seat back.

Model Development

Two different types of models were developed: duration and response. The duration models predicted a response duration given a peak sled acceleration (PSA). The response models predicted a time series response given an exposure pulse. Each model was developed using the head flail response and exposure data obtained from the BDR. Models were developed specific to each impact direction and primary displacements of interest: vertical for all impact directions; AP for frontal, axial, oblique, and off-axis impacts; and lateral for lateral and oblique impacts. For each impact direction, only tests with similar exposure pulse shapes were included in model development.

Duration models.

The exposure data from the BDR were used to develop models that predict the duration of the human response given a PSA. The duration models were calculated using linear regression of the PSA and total response duration for the trimmed mean response of all HRV tests at the corresponding PSA level (Equation 1). The trimmed mean response, defined by Olszko et al. (2021) as the corridor mean, was trimmed in duration to a loss of 10% or 3 of the total tests at time zero. Each impact direction was modeled separately. Thus, the duration model for each impact direction consists of a single linear regression model. The input into the model is a PSA value, and the output is the predicted response duration.

The duration model is summarized as

$$d = m_d * a + b_d \tag{1}$$

where d is the predicted response duration, a is the PSA value (time invariant), m_d is the slope, and b_d is the y-intercept. Each model was evaluated numerically with R-squared.

Response models.

The exposure and response data from the BDR were used to develop models that predict the head flail response given an input pulse. The response models were calculated using linear regression of the instantaneous sled velocity and response at each time point (Equations 2 – 4). The x (AP), y (lateral), and z (vertical) components of the response were modeled separately, where lateral camera views included x and z response components and frontal camera views included y and z response components. Each impact direction was modeled separately. Thus, the response model for each direction consists of a series of linear regression models at each time point. The input into the model is a velocity pulse, and the output is the predicted response, x, y, or z component, at each time point.

For every time point, t, the response models are summarized as

$$x(t) = m_x(t) * v(t) + b_x(t) \tag{2}$$

$$y(t) = m_y(t) * v(t) + b_y(t) \tag{3}$$

$$z(t) = m_z(t) * v(t) + b_z(t) \tag{4}$$

which can be simplified to

$$x = m_x * v + b_x \tag{5}$$

$$y = m_y * v + b_y \tag{6}$$

$$z = m_z * v + b_z \tag{7}$$

where x, y, and z are components of the predicted response, v is the instantaneous velocity, m_x, m_y, and m_z are the respective slopes for each component, and b_x , b_y, and b_z are the respective y-intercepts for each component.

Predicted response duration.

The predicted response data were trimmed according to the duration model or the duration of the corresponding corridor mean. Trimming according to the duration model was used for impact directions with a corresponding duration model with an R-squared value greater than 0.75. Trimming according to the corresponding corridor mean was used for all other impact directions.

When trimmed according to the duration model, the corresponding pulse PSA was input into the duration model, and the predicted duration was calculated. The predicted response data were trimmed to that predicted duration. When trimmed according to the corridor mean, the corridor with the nearest pulse PSA was identified, and the predicted response data were trimmed to the duration of that corridor mean. This method of trimming the predicted response was selected to minimize any artifacts in the predicted response due to poor model performance from a low number of tests. In other words, the predicted response was trimmed to a duration where the confidence in the model performance is highest, and a true response may have a shorter or longer duration.

Verification.

The response model was verified using the BDR HRV data that were used to build the response model. For each BDR test that was used in model development, the exposure pulse was input into the response model to calculate the predicted response. The predicted responses were trimmed as described above; the trimmed predicted responses typically had a shorter duration than the experimental response. The differences between the predicted response and BDR experimental response were calculated within the duration of the shorter response. For the frontal, axial, oblique, and off-axis impact directions, differences were calculated for the maximum AP and minimum vertical positions within the defined duration. For the lateral and oblique impact directions, differences were calculated for the maximum lateral and minimum vertical positions within the defined duration. The model was characterized as overpredicting the response when the difference was greater than zero for comparisons of maximum AP and lateral positions. The model was characterized as underpredicting when the difference was greater than zero for comparison of the minimum vertical positions.

Validation.

The response model was validated using experimental HRV and post-mortem human subject (PMHS) data. The experimental or representative experimental exposure was input into the response model to calculate the predicted response. The predicted response and experimental response differences were calculated within the shorter response duration. Differences were calculated for the maximum AP and minimum vertical positions within the defined duration for the frontal, axial, oblique, and off-axis impact directions. For the lateral and oblique impact directions, differences were calculated for the maximum lateral and minimum vertical positions within the defined duration. The model was characterized as overpredicting the response when the difference was greater than zero for comparisons of maximum AP and lateral positions. The model was characterized as underpredicting when the difference was greater than zero for comparison of the minimum vertical positions.

Optimally, the validation tests would have the same or a similar exposure pulse as the tests used to build the model. Having similar exposure pulses would validate the model for any other similar exposures. However, all 323 tests from the BDR HRV dataset with similar exposure pulses were used to develop the response models in order to maximize the number of tests at each exposure level used to develop the model; none were set aside specifically for validation. Thus, other experimental tests with different exposure characteristics were used for validation; experimental HRV and PMHS data were obtained from both the BDR HRV dataset and other experimental datasets. These tests also were used to inform the limitations of the model for predicting responses for other exposure pulses. More specifically, comparison to these tests informs the expected amount of difference in the response for a given difference in the exposure pulse input.

BDR NBDL HRV data.

The response model was validated using the remaining BDR HRV data that were not used to build the response model. These remaining data were not used in developing the response model because the exposure pulses were different from the selected tests used in model development. Models for all impact directions except off-axis were validated with BDR HRV data; no remaining data for off-axis tests existed in the BDR HRV dataset at the time. The experimental exposure pulses were input into the response models, and the head flail response was predicted for each pulse.

Other experimental data.

Experimental data from other sources were also considered for response model validation. The other experimental data sources included published literature, the National Highway Transportation Safety Administration (NHTSA) database, and unpublished data from tests conducted by USAARL on the vertical acceleration tower (VAT).

Exposure data and head displacement data were extracted for tests from each source. Additional parameters were also extracted for each test, including restraint type, seat recline position, and injury outcome. These parameters likely affected the response and were used to inform differences between the predicted and experimental responses.

Literature.

Published literature was reviewed for head displacement data from whole-body sled tests with HRV or PMHS. If publications had multiple tests with head displacement data, only a subset of those tests was selected. Then, the representative pulses were input into each respective response model, and the head flail response was predicted for each pulse.

NHTSA.

The NHTSA database was reviewed for head displacement data from whole-body sled tests with PMHS. Tests were selected that were similar to BDR HRV exposures. The sled acceleration sensor data and tracked head displacement data were extracted for each test. The head displacement data were synced according to time zero using the resultant head displacement, similar to the procedure applied by Olszko et al. (2021) to the BDR HRV phototarget data, then adjusted to match the seat origin and initial position of the BDR HRV data. Then, the sled accelerations were input into the response models, and the head flail response was predicted for each pulse.

USAARL VAT.

Previously collected data from the USAARL VAT whole-body PMHS tests were obtained for 12 tests. Sled acceleration sensor data and tracked head displacement data were extracted. The head displacement data were synced according to time zero using the resultant head displacement, similar to the procedure applied by Olszko et al. (2021) to the BDR HRV phototarget data, then adjusted to match the seat origin and initial position of the BDR HRV data. Then, the sled accelerations were input into the response models, and the head flail response was predicted for each pulse.

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Results

A total of 323 HRV tests were used for model development (Table 1). Tests encompassed the frontal, axial, lateral, oblique, and off-axis impact directions, and each impact direction had at least 30 tests. The PSA for all tests spanned from 3 to 15 G (Appendix B) and were grouped according to similar pulse characteristics, including peak sled velocity (PSV) and rate of onset (ROO). Duration and response models were developed for each impact direction for the primary displacements of interest, resulting in seven models of each type (duration and response) for a total of 14 models. Duration models were considered valid for frontal, lateral, and axial impact. For these impact directions, R-squared values were above 0.75. The side camera view for oblique impact was also valid, but the front camera view was not (Appendix C). Thus, only frontal, lateral, and axial impact direction models were evaluated through verification and validation.

Table 1. Summary of Tests Used for Response Models

Direction	Camera View	Number of Tests	PSA (G)			PSV (m/s)			ROO 50-80% (G/s)		
			Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.
-X	Side	32	11	5	15	14	6	18	438	190	719
+Z	Side	38	7	5	12	5	4	8	851	406	1465
+Y	Front	79	8	5	10	3	2	3	257	142	433
-X+Y	Front	47	7	5	10	10	7	13	214	144	293
-X+Y	Side	46	7	5	10	10	7	13	215	144	293
+Z-X10	Side	90	5	3	7	8	5	11	249	174	352
+Z+X30	Side	37	5	3	8	8	5	12	197	95	333

Note. A total number of 323 unique tests were used for response model development; for most tests, only one camera view was used for analysis; for tests in the oblique (-X+Y) direction, both front and side camera views were used. Min. = minimum; Max. = maximum; m/s = meters per second; G/s = Gs per second

Verification

Predicted responses for the frontal, axial, and lateral impact directions were compared with the families of experimental responses used to develop the response models. Figure 1 shows predicted and experimental responses for all exposure levels for the three impact directions. Comparisons of predicted and experimental responses for individual exposure levels (e.g., 5 G, 10 G, etc.) for the frontal, axial, and lateral impact directions are provided in Appendix D. The predicted responses fell within the families of experimental responses used to develop the models (Figure 1 and Figures D1-D3). The predicted responses tended to fall near the center of each family of experimental responses. The verification also shows the impact trimming the response duration has on response similarity. For the axial impact direction model, the predicted responses are shorter in duration than the actual experimental responses.

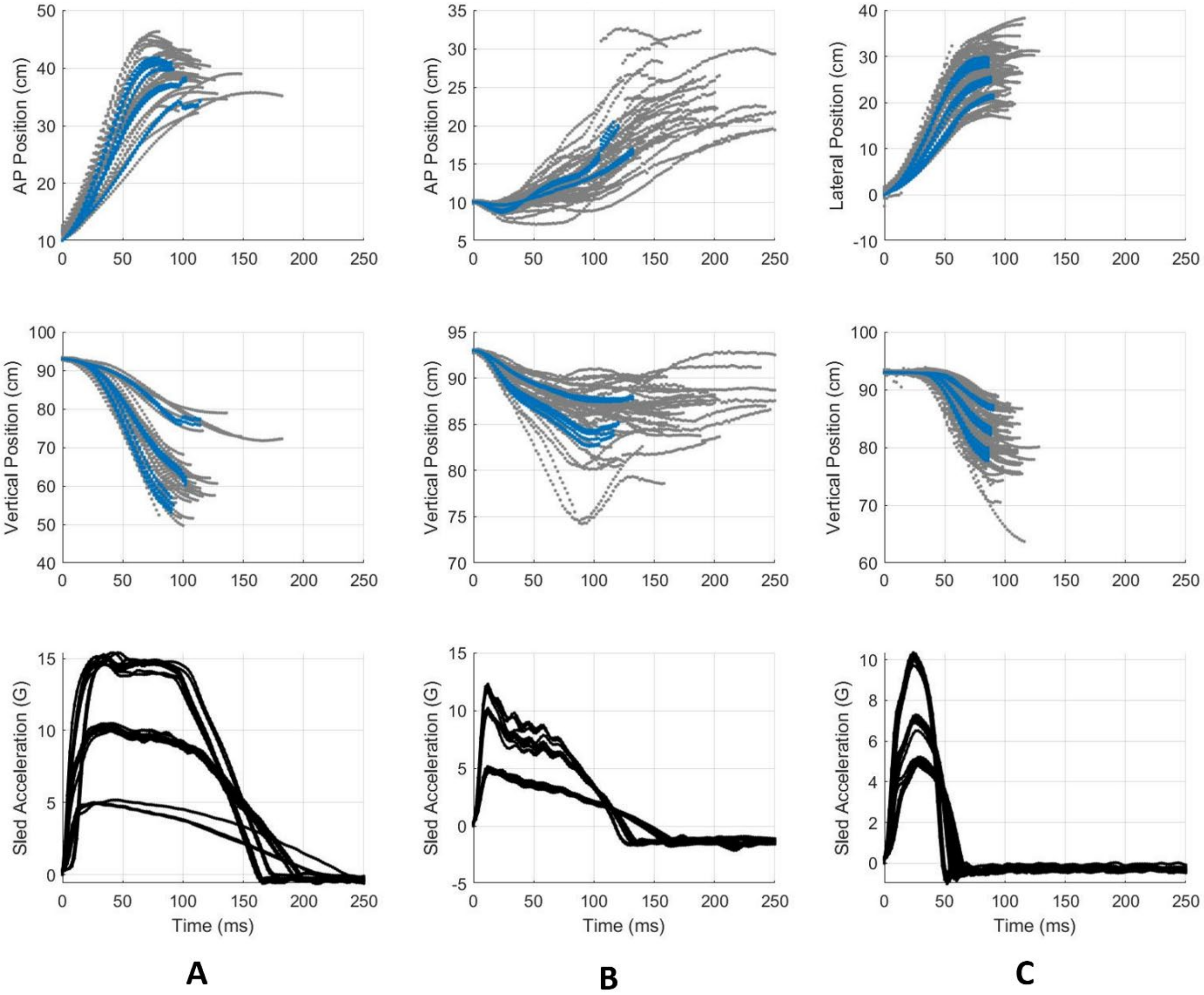

Figure 1. Time-based plots comparing predicted and experimental responses for BDR HRV verification tests. Predicted and experimental responses are represented by the blue and gray markers, respectively. (A) Frontal, (B) axial, and (C) lateral impact directions were evaluated for verification. The experimental sled acceleration pulses (black line) were integrated to provide response model input velocity profiles for each BDR HRV test.

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The differences between the maximum displacements from the predicted and experimental responses were quantified (Table 2). For each model, the mean difference in AP or lateral displacement was less than 3 cm, and the mean difference in vertical displacement was less than 2 cm (Table 2). The largest mean difference in AP or lateral displacement corresponded to the frontal impact direction model, while the largest mean difference in vertical displacement corresponded to the axial impact direction model. The mean difference between predicted and experimental responses was 0 cm for vertical displacement for the frontal and lateral impact directions and for the AP direction for the axial impact response; while the mean difference for each was 0 cm, the response models for each of these direction overpredicted the experimental response for at least 50% of the tests for each (Table 2).

Table 2. Summary of Response Model Verification Results

Direction	**Position**	**Number of Tests**	**Number of OP Tests**	**Percent of OP Tests**	**Mean**	**Std.**	**Median**	**Max.**	**Min.**
					cm				
-X	AP	32	9	28%	-0.02	0.03	-0.03	0.07	-0.06
-X	Vertical	32	16	50%	0.00	0.03	0.00	0.05	-0.07
+Z	AP	38	25	66%	0.00	0.03	0.01	0.08	-0.12
+Z	Vertical	38	18	47%	0.01	0.03	0.01	0.10	-0.04
+Y	Lateral	79	32	41%	-0.01	0.03	-0.01	0.05	-0.10
+Y	Vertical	79	43	54%	0.00	0.02	0.00	0.08	-0.05

Note. The number of overprediction (OP) tests and the percent of OP tests were calculated with respect to the total number of tests used to develop the response model. The summary statistics were calculated for the differences between the predicted and experimental responses. A negative median indicates that the model is usually underpredicted for AP and lateral position. A positive median indicates that the model is usually underpredicted for the vertical position. Standard deviation is abbreviated as Std., and centimeters is abbreviated as cm.

Validation

A total of 312 BDR HRV tests were used for validation (Table 3). Tests encompassed the frontal, axial, and lateral impact directions. The frontal and lateral directions had over 140 tests each, while the axial test had 22 tests. The PSA for all tests spanned from 5 to 15 G (Table 3) and were grouped according to similar pulse characteristics, including PSV and ROO.

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Table 3. Summary of BDR HRV Tests Used for Response Model Validation

Direction	**Camera View**	**Number of Tests**	**PSA (G)**			**PSV (m/s)**			**ROO 50-80% (G/s)**		
			Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.
-X	Side	143	10	5	15	12	3	18	346	123	968
+Z	Side	22	5	5	10	5	5	10	105	61	293
+Y	Front	147	6	5	7	7	6	7	198	118	393

Note. m/s = meters per second; G/s = Gs per second

Response models for the frontal, axial, and lateral impact directions were used to predict HRV responses for BDR HRV tests not used for model development. For these tests, the predicted and experimental responses are plotted together for each impact direction (Figure 2). Predicted and experimental responses are also plotted for each exposure condition for the frontal, axial, and lateral impact directions in Appendix E. Generally, the predicted responses fell within the family of experimental responses (Figure 2). In most cases, the predicted response fell near the center of the family of experimental responses, but some predicted response fell near the right-most portion of the experimental responses (Figure E1-E4). The validation data also shows the impact trimming the response duration has on response similarity. For all impact direction models, the predicted responses are shorter in duration than the actual experimental responses.

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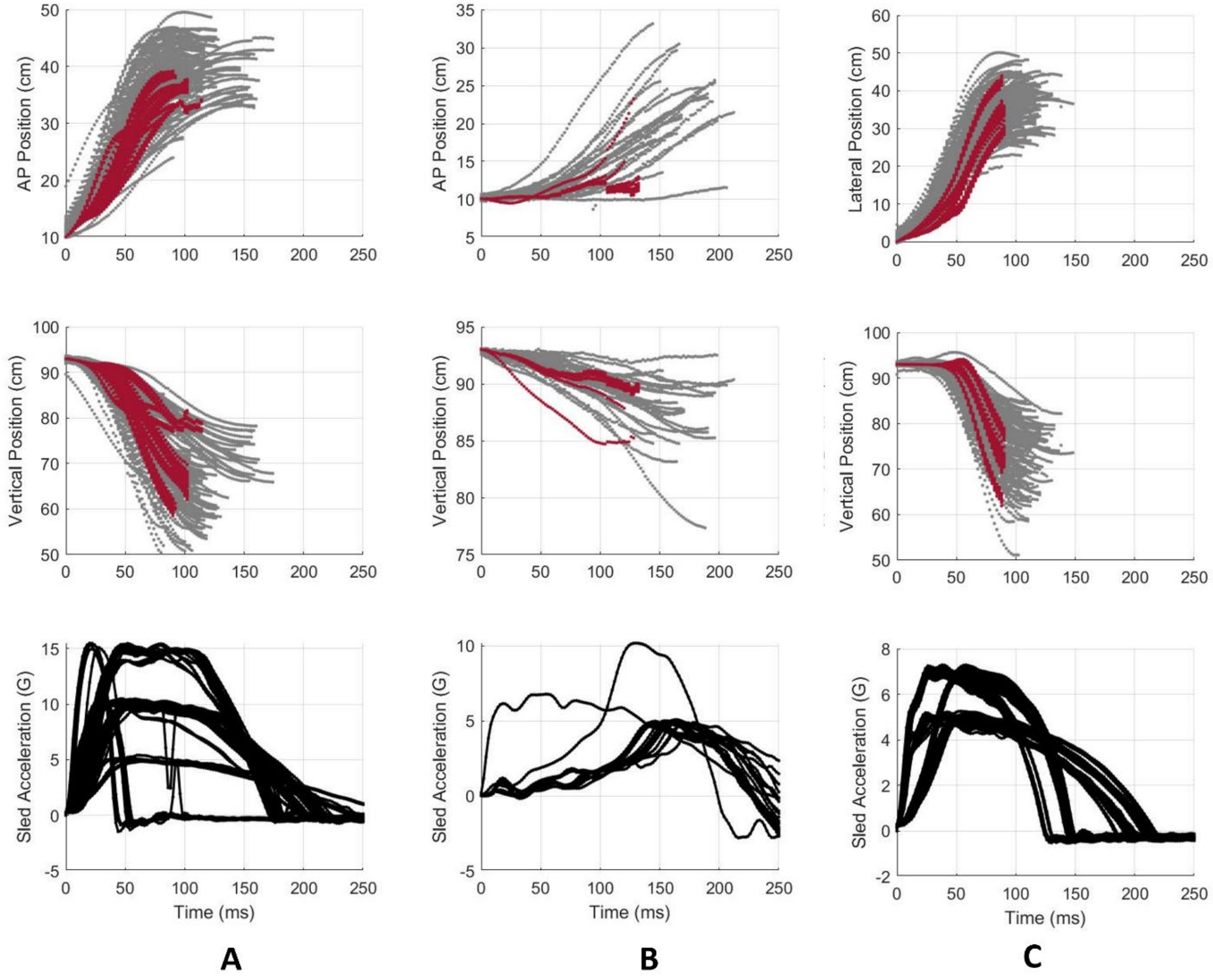

Figure 2. Time-based plots comparing predicted and experimental responses for HRV validation tests. Predicted and experimental responses are represented by the red and gray markers, respectively. Frontal (A), axial (B), and lateral (C) impact directions were evaluated for validation. The experimental sled acceleration pulses (black line) were integrated to provide response model input velocity profiles for each BDR HRV validation test.

For each model, the mean difference in AP or lateral displacement was less than 7 cm, and the mean difference in vertical displacement was less than 5 cm (Table 4). The largest mean difference in AP or lateral displacement corresponded to the axial impact direction model, while the largest mean difference in vertical displacement corresponded to the lateral impact direction model.

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Table 4. Summary of BDR HRV Validation Results

Direction	Position	Number of Tests	Number of OP tests	Percent of OP Tests	Mean	Std.	Median	Max.	Min.
					cm				
-X	AP	143	35	24%	-0.03	0.04	-0.03	0.09	-0.12
-X	Vertical	143	63	44%	0.01	0.04	0.02	0.14	-0.08
+Z	AP	22	2	9%	-0.05	0.05	-0.05	0.02	-0.20
+Z	Vertical	22	8	36%	0.01	0.02	0.01	0.05	-0.03
+Y	Lateral	147	65	44%	-0.01	0.06	-0.01	0.14	-0.13
+Y	Vertical	147	126	86%	-0.04	0.05	-0.03	0.10	-0.19

Note. The number of overprediction (OP) tests and the percent of OP tests were calculated with respect to the total number of tests used to validate the response model. The summary statistics were calculated for the differences between the predicted and experimental responses. For AP and lateral position, a negative median indicates that the model is usually underpredicted. For the vertical position, a positive median indicates that the model is usually underpredicted. Standard deviation is abbreviated as Std., and centimeters is abbreviated as cm.

Relationships between exposure characteristics of PSA, PSV, and ROO and model performance were identified (Appendix F). For the frontal, axial, and lateral impact directions, the differences between predicted and experimental responses were dependent on all three exposure characteristics (Figures F1, F2, and F3, respectively). Generally, ROO had the greatest influence on the calculated differences for the three impact directions, the lateral impact exhibiting the largest dependence. PSV and PSA also influenced the differences between predicted and experimental responses but not to the same extent as ROO.

Other experimental data.

A total of 43 tests with head displacement data available were selected for validation (Table 5). Though the aim was to identify tests similar to the BDR HRV tests, all identified tests varied from the BDR HRV tests with respect to exposure pulse (PSA and PSV), test setup (seat recline and restraint types), and injury outcome. Also, HRV data were only available for the frontal impact direction, while only PMHS tests were available for the remaining directions.

Large differences between the predicted and experimental response were observed for most tests. Select examples of the response differences are presented in Figure 3. These large response differences are likely due to the differences in test setup and subject types between the BDR HRV dataset and the other experimental data. Therefore, these differences are not included in this report as they are not considered an accurate reflection of the response model performance.

Table 5. Overview of Validation Tests Selected from Other Datasets

Direction	Tests	PSA (G)		Subject Type	Seat Recline	Restraint Types	Injury Status	Topic	Data Source
		Min.	Max.						
Frontal	5	19	20	HRV	Yes	ACRS	No	AV	Brinkley, 1977
Frontal	6	9	10	HRV	Yes	(1) H, LB, negGs (2) H, LB	No	AV	Hearon et al., 1983
Frontal	3	13	13	PMHS	Yes	SB	No?	AUT	Forman et al., 2006
Frontal	6	21	21	PMHS	Yes	(1) SB (2) FL PT SB	Yes	AUT	Forman et al., 2009
Frontal	1	12	12	PMHS	Yes	SB	Yes	AUT	NHSTA UMTRI
Lateral	4	16	16	PMHS	Yes	ShB, BC LB, LAR	Yes	AV	Humm et al., 2016
Oblique	4	16	16	PMHS	Yes	(1) BC LB, LB (2) LB, RAR	Yes	AV	Humm et al., 2016
Oblique	1	10	10	PMHS	Yes	BC LB, LB	No	AV	Humm, 2020
Lateral	1	12	12	PMHS	Yes	SB	Yes	AUT	NHTSA MCW
Axial	12	16	22	PMHS	No	H	Yes	AV	USAARL VAT

Note. Validation tests were either automotive (AUT) or aviation (AV) related. Restraint types include air cushion restraint system (ACRS), body-centered lap belt (BC LB), force-limiting pre-tensioning seatbelt (FL PT SB), aviation harness (H), left arm rest (LAR), lap belt (LB), negative G strap (negGS), right arm rest (RAR), automotive seatbelt (SB), and shoulder belt (ShB). If more than one combination of restraints were used for tests of a given data source, the combinations are indicated as "(1)" or "(2)." All BDR HRV tests were conducted with a 90-degree seat back and aviation harness. Lateral and oblique BDR HRV tests included a side panel that could limit the lateral displacement of the subject. All BDR HRV tests were considered non-injurious.

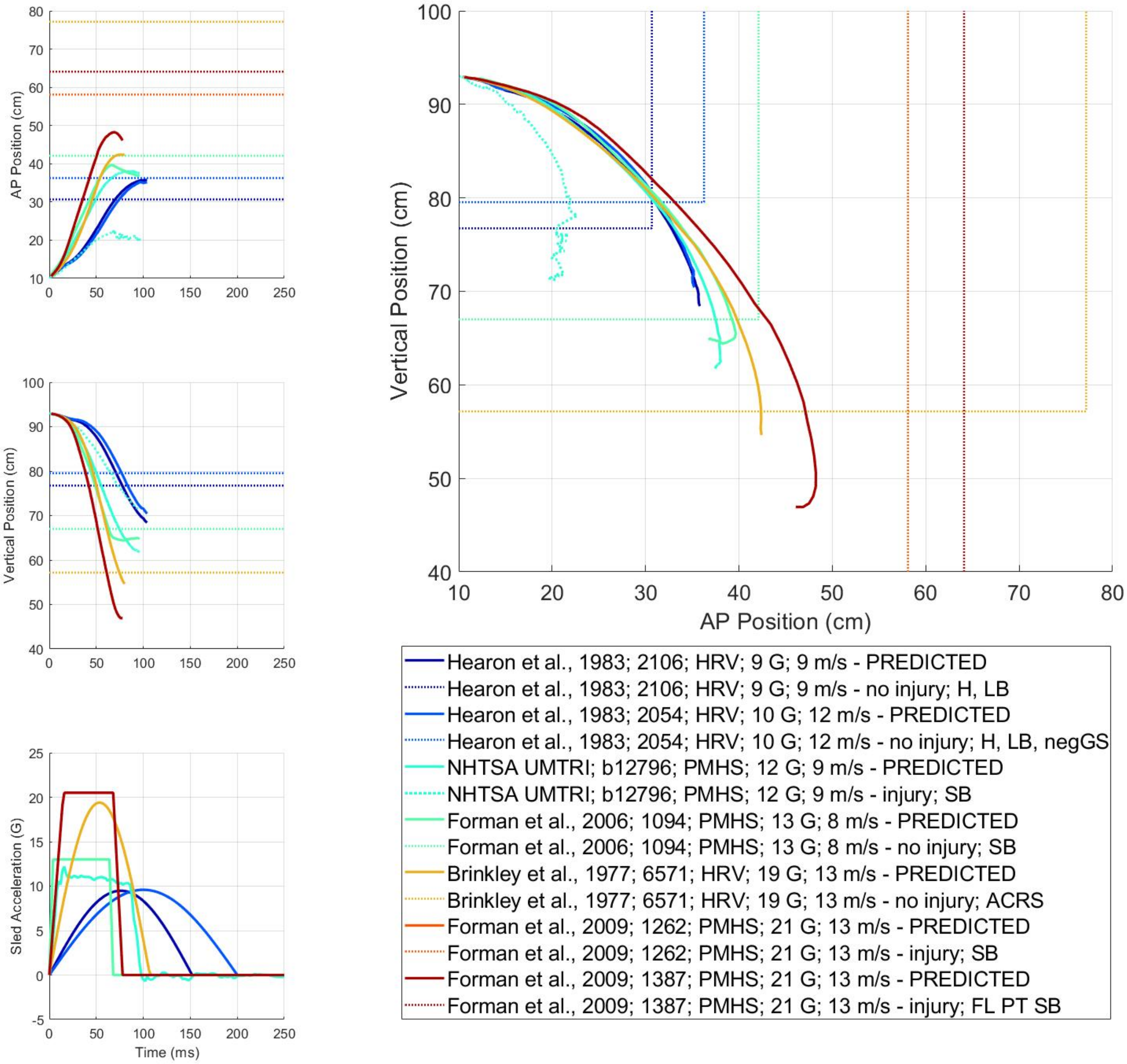

Figure 3. Comparison of predicted and experimental responses for selected tests. All tests are frontal impact tests from the literature or the NHTSA database. For each test, the predicted response is represented by the solid line, and the experimental response is represented by the dotted line. For the NHTSA test, the input pulse into the model was identical to the experimental pulse integrated to velocity; for the remaining tests from literature, the input pulse was a simplified, representative acceleration pulse that was integrated to velocity. Because time series data were not extracted for literature tests, the lines plotted represent the bounds of the response formed by the maximum AP or vertical positions. The NHTSA head displacement was adjusted to exclude torso (sternum) displacement; the non-adjusted NHTSA head displacement would exceed the AP position of the model's predicted response.

Discussion

Response models for the frontal, axial, and lateral impact directions were shown to accurately predict the BDR HRV responses that were used to develop the model. For each impact direction, predicted responses fall inside the families of measured HRV response curves (Figure 1). Additionally, for each impact direction, the average difference between the predicted and measured responses for AP and lateral displacements was less than 3 cm. The mean difference in vertical displacements was less than 2 cm (Table 2). These data indicate that the response models developed for the frontal, axial, and lateral impact directions were verified to reasonably predict the HRV response used to develop the model.

The BDR HRV responses that were not included in the development of the response models were used to validate the response models for the frontal, axial, and lateral impact directions. These HRV responses were collected during experiments performed on the same test devices, using the same test fixtures and restraint systems and, in some cases, involved the same HRVs as the runs used to develop the response models. The difference between the two sets of BDR HRV responses is that the validation set was conducted at different PSAs, PSVs, and ROOs (Table 3). The similarity in boundary conditions made the additional BDR HRV dataset the most appropriate set of data available to verify the response models.

Response models for the frontal, axial, and lateral impact directions were also shown to reasonably predict BDR HRV responses that were not used to develop the models. For each impact direction, predicted responses fell within the family of experimental responses, with some predicted responses falling near the right-most extreme of the family of experimental responses. (Figure 2 and Figures E1-E5). Response models for the frontal, axial, and lateral impact directions did produce variations between the predicted and measured displacements in the AP, lateral, and vertical directions. The average difference between the predicted and measured responses for AP and lateral displacements was less than 7 cm. The mean difference in vertical displacements was less than 5 cm (Table 4). The differences in predicted and experimental response may be partially due to the duration of the predicted responses, which were typically shorter than the experimental responses.

Additional validation of the response models was attempted using data available from literature, the NHTSA database, and USAARL. Figure 3 shows large differences between model predicted responses and measured displacements taken from these other data sources. These large response differences are likely due to the differences in test setup and subject types between the BDR HRV dataset and the other experimental data. As an example, Brinkley (1977) tested human volunteers seated in a reclined seat at approximately 12 degrees, while NBDL HRVs were seated in an upright, non-reclined position. Also, NBDL HRVs were well restrained using aviation-style harnesses; the human volunteers in the Brinkley (1977) were not restrained using conventional restraints; rather, these volunteers were restrained by an oversized airbag. As a result of differences like these, the displacements obtained from literature, the NHTSA database, and other USAARL studies were determined to be inappropriate for validating the response model prediction.

The response models developed for the frontal, axial, and lateral impact directions were verified and validated to predict the head flail response of seated, well-restrained occupants undergoing accelerative events of up to 15 G in the frontal and axial directions and 10 G in the lateral direction. These verified and validated response models allow human head flail response to input accelerations outside those available in the BDR dataset to be predicted. These response models can be used as a tool to delethalize aircraft cockpit and cabin interiors, as well as other vehicles in which occupants are seated upright and well-restrained.

The difference between predicted and experimental responses was shown to be dependent on parameters PSA, PSV, and ROO. For all impact directions, the differences between predicted and experimental responses showed a dependence on all three parameters, with some impact directions showing a greater dependence on individual parameters than others (Appendix F). These dependences indicated that more accurate response models could be generated using a multivariate regression, considering PSV and ROO in addition to PSA. Rapo et al. (2017) used this type of analysis when developing a model for predicting the effects of head-supported mass wearer performance and acute injury risk.

Limitations

The BDR NBDL collection is comprehensive, as it includes the complete set of input variables and subject response variables, including acceleration data, displacement data, subject subjective responses, and objective physiological and medical assessments of subjects (Schmidt et al., 2009). The BDR includes these data for HRVs, non-human primates (NHPs), and anthropomorphic test devices (ATDs). This makes it a unique dataset for evaluating biomechanics in accelerative environments.

However, the uniqueness of the BDR data means that there are few, if any, comparable datasets. There were limited available data that were appropriate for validation of the response model. Many publications only provided summarized or averaged data, or no data at all, rather than tabulated results. Plotted data required numerical processing to retrieve data points. Some of the data provided only included acceleration data rather than displacement values. Additionally, variations in test setup and subject type made any comparison to the model predicted response representative of a well-restrained living human occupant challenging.

One of the limitations of the developed response models includes the method for determining predicted response duration. Predicted responses were trimmed to the corridor mean, either indirectly using the duration model or directly. Trimming of predicted responses means that the full expected response may not be represented by the predicted response output of the model. Other methods of determining the duration of the predicted response were considered, but the one used here was selected because it limited the possibility of erroneous predicted response data.

Future Work

Future work could include analyzing additional data, more complex modeling, and predicting the response for higher, operationally relevant exposure levels. The BDR NBDL collection includes additional HRV tests that were not evaluated for this report. These additional HRV tests could fill gaps in the exposure characteristics and be leveraged to develop a more robust model. Additionally, the modeling approach could use relationships between the HRV and ATD tests from the BDR NBDL collection. Furthermore, the linear regression modeling approach used here may be too simple to represent the variation in exposure and subject characteristics. For example, Rapo et al. (2017) used a quadratic least squares fit for predicting the magnitudes of neck injury metrics, where a different model was developed for each injury metric. This approach could be used with the BDR HRV tests to develop predictions based on models specific to each exposure parameter (e.g., PSA, PSV, and ROO). Lastly, a validated model could predict the occupant response for higher exposure levels more representative of aircraft crash dynamics.

Conclusions

The response models were verified to accurately predict the HRV response used to develop the model.

The response models were validated to reasonably predict AP, lateral, and vertical displacements for BDR HRV tests with similar boundary conditions but different input parameters than those of the BDR HRV tests used to develop the response model.

The response models were not shown to be valid for predicting subject responses to higher sled acceleration levels and velocity changes found in the literature. The primary reason for this is the differences in initial and boundary conditions between the NBDL dataset and the datasets from the literature.

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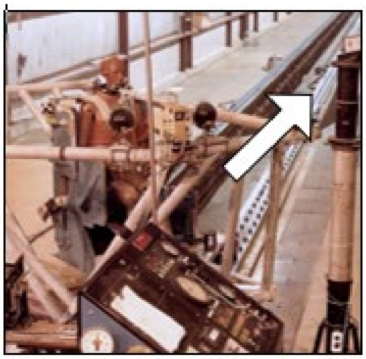
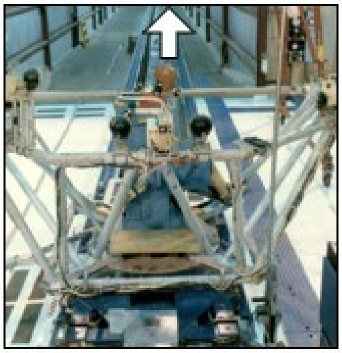
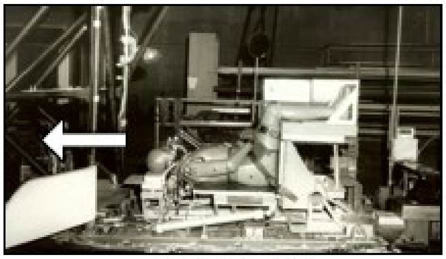
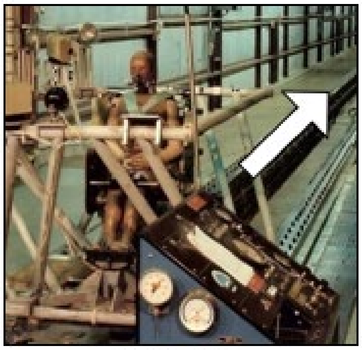
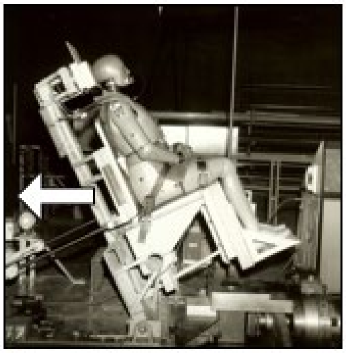
Appendix A. NBDL HRV Sled Test Orientations


-X+Y (Oblique)
546 Human (max 13 G)


+/-Y (Lateral)
923 Human (max 11 G)


+Z (Axial, HA)
380 Human (max 13 G)


-X (Frontal)
1,163 Human (max 16 G)


-X+Z (Frontal, Pitched)
135 Human (max 8 G)

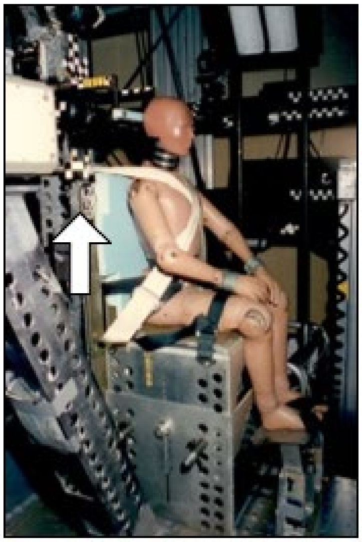

+Z (Axial, VA)
392 Human (max 12 G)

Figure A1. Examples of the acceleration directions and subject positioning for each direction. Number of HRV runs and the maximum Gs reached for HRV exposures are also included. Note: -X+Z impact direction notation is used in this figure to indicate pitched runs, but in the main body of this report, we will use the +Z-X impact direction to indicate that the primary vector of impact to the subject was axial (the subjects were primarily supine rather than upright) and the angle of the pitch is the degrees from horizontal (i.e., +Z-X10 or +Z-X30).

Appendix B. Average Exposure Pulse for Tests used in Model Development

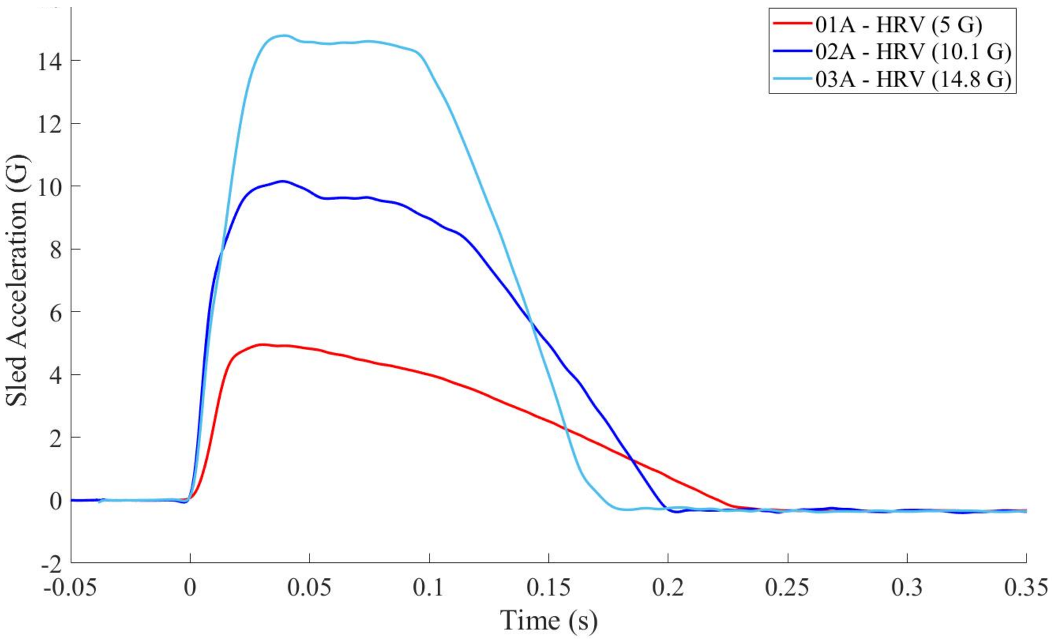


Figure B1. Match group sled acceleration pulses for the frontal (-X) impact direction. For each match group, the mean sled acceleration pulse and the maximum acceleration of that pulse for all HRV tests within a match group were calculated.

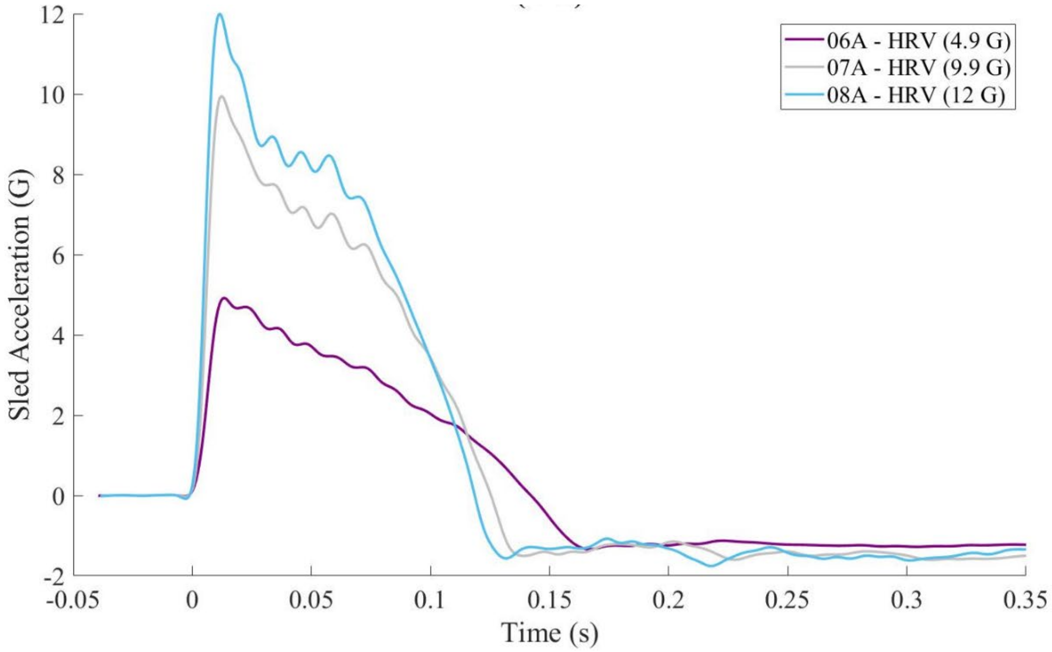


Figure B2. Match group sled acceleration pulses for the axial (+Z) impact direction. For each match group, the mean sled acceleration pulse and the maximum acceleration of that pulse for all HRV tests within a match group were calculated.

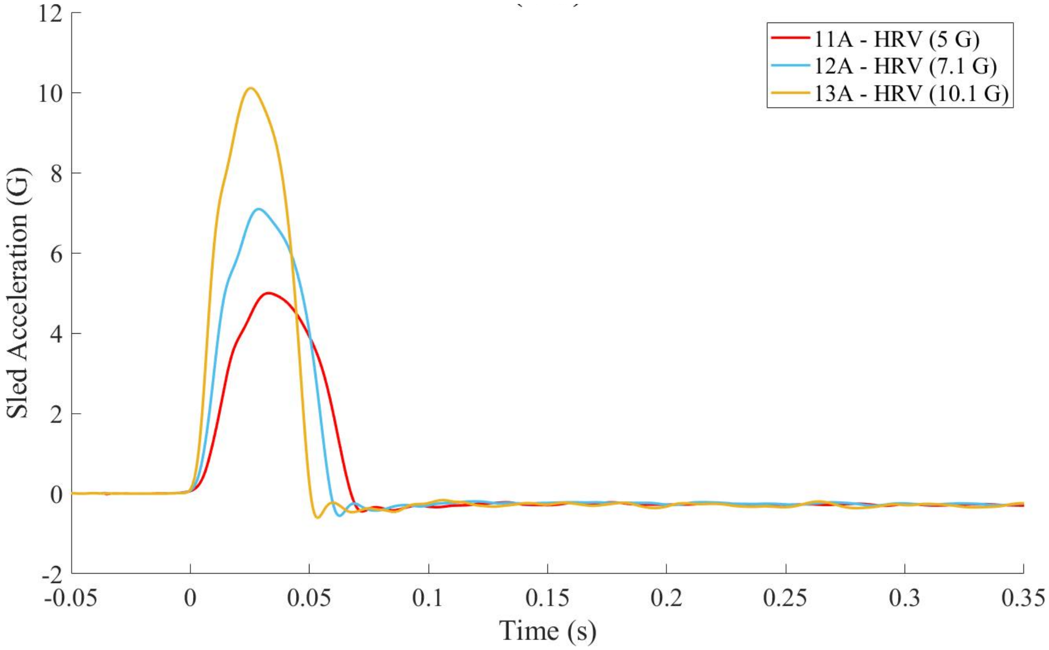


Figure B3. Match group sled acceleration pulses for the lateral (+Y) impact direction. For each match group, the mean sled acceleration pulse and the maximum acceleration of that pulse for all HRV tests within a match group were calculated.

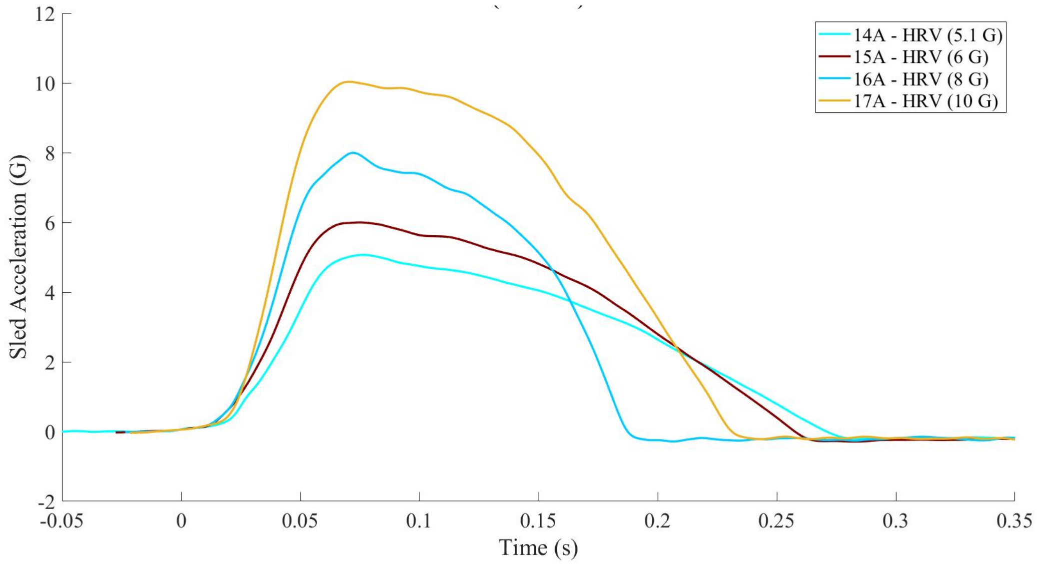


Figure B4. Match group sled acceleration pulses for the oblique (-X+Y) impact direction.For each match group, the mean sled acceleration pulse and the maximum acceleration of that pulse for all HRV tests within a match group were calculated.

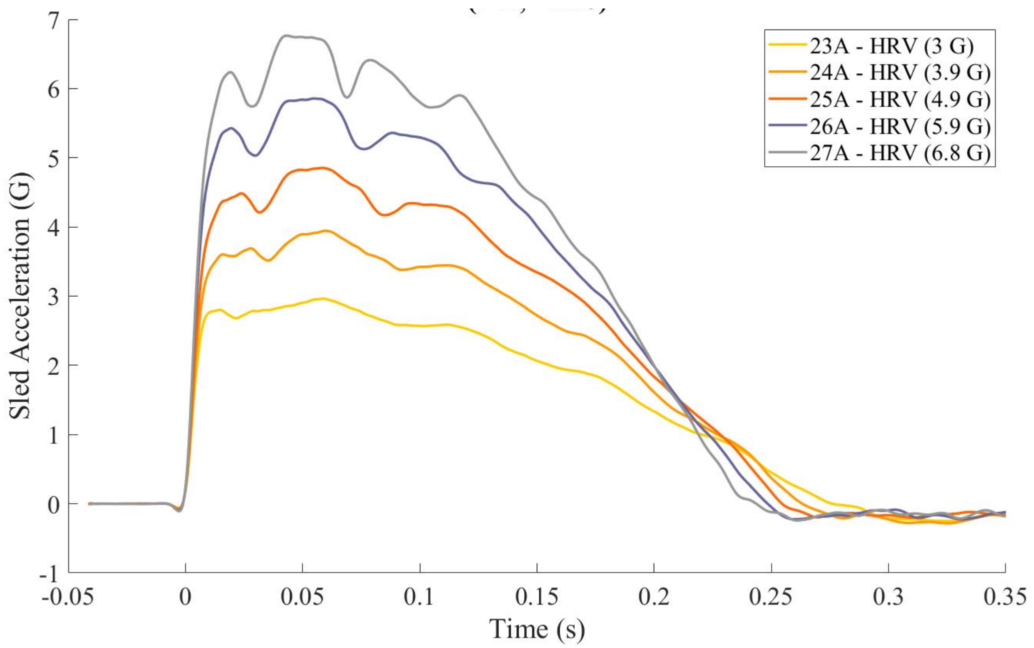


Figure B5. Match group sled acceleration pulses for the off-axis (+Z-X10) impact direction.For each match group, the mean sled acceleration pulse and the maximum acceleration of that pulse for all HRV tests within a matched group were calculated.

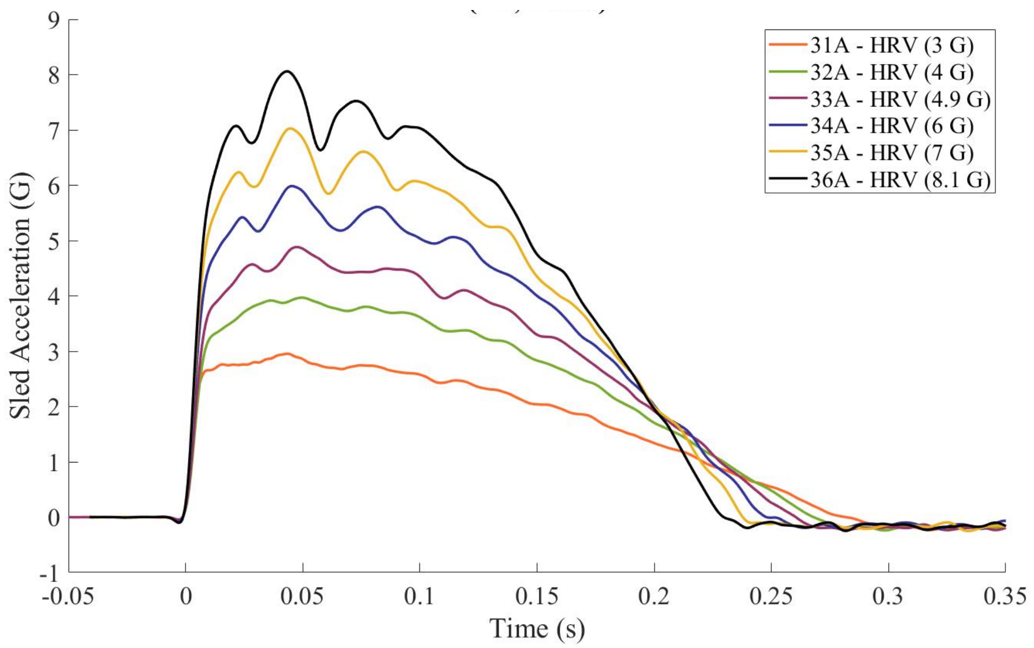


Figure B6. Match group sled acceleration pulses for the off-axis (+Z-X30) impact direction.For each match group, the mean sled acceleration pulse and the maximum acceleration of that pulse for all HRV tests within a match group were calculated.

Appendix C. Duration Models

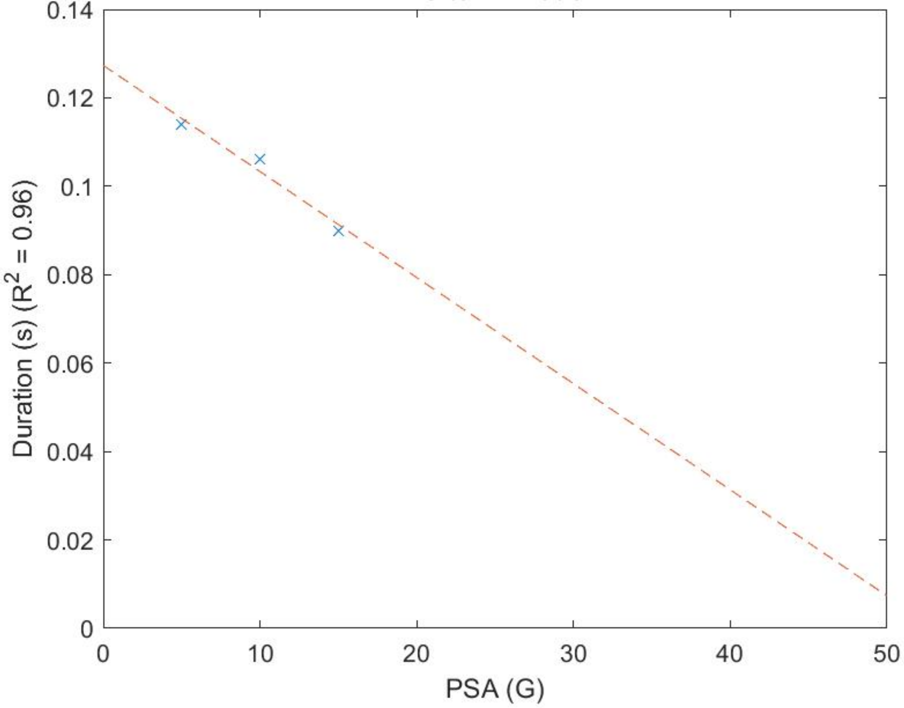


Figure C1. Linear regression duration model for frontal (-X) impact direction. PSA is the peak sled acceleration.

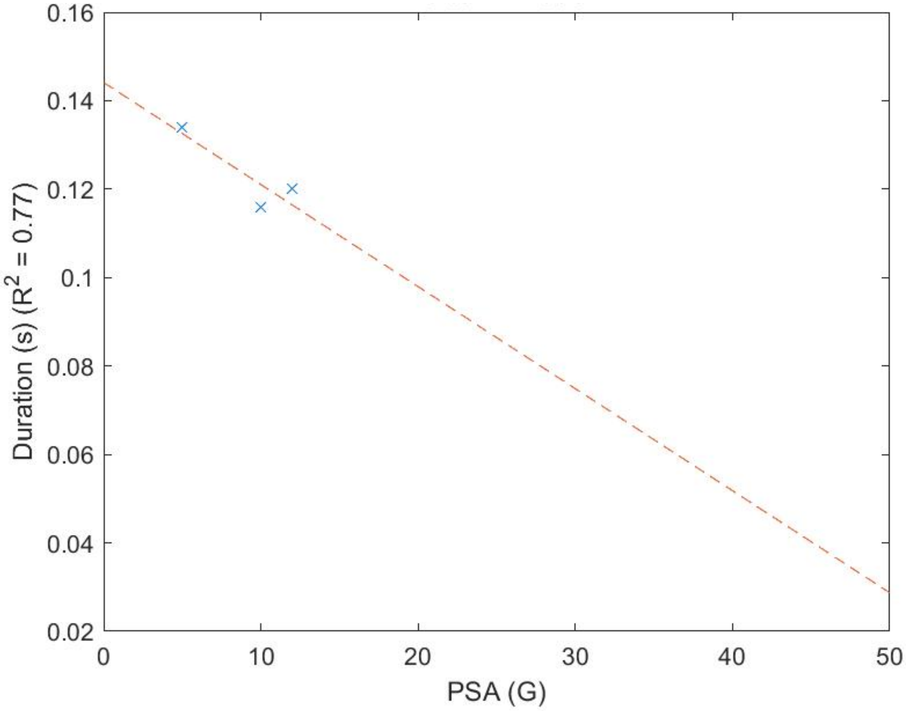


Figure C2. Linear regression duration model for axial (+Z) impact direction. PSA is the peak sled acceleration.

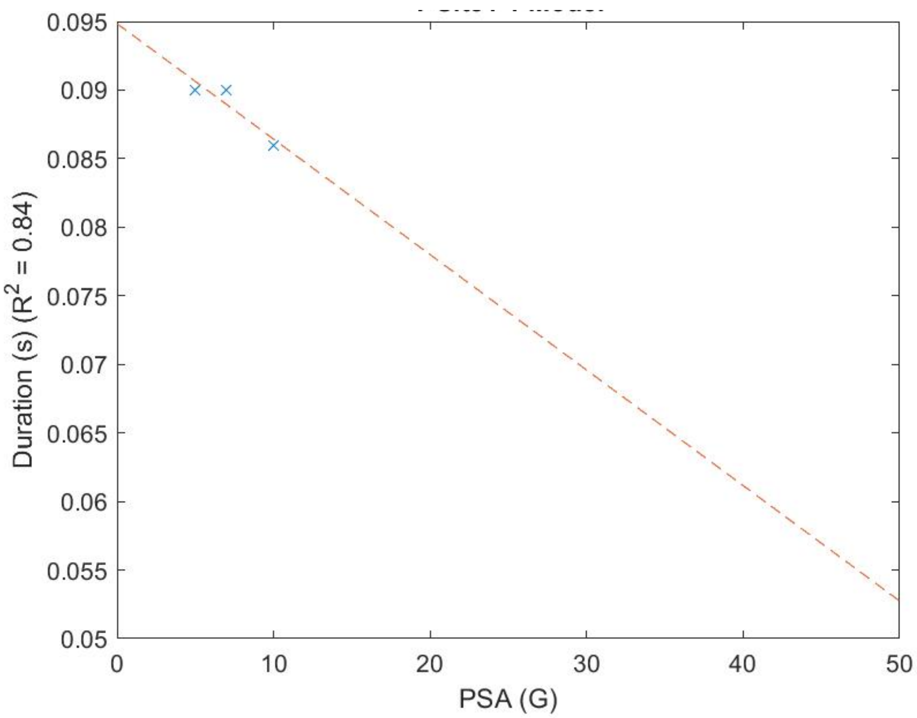


Figure C3. Linear regression duration model for lateral (+Y) impact direction. PSA is the peak sled acceleration.

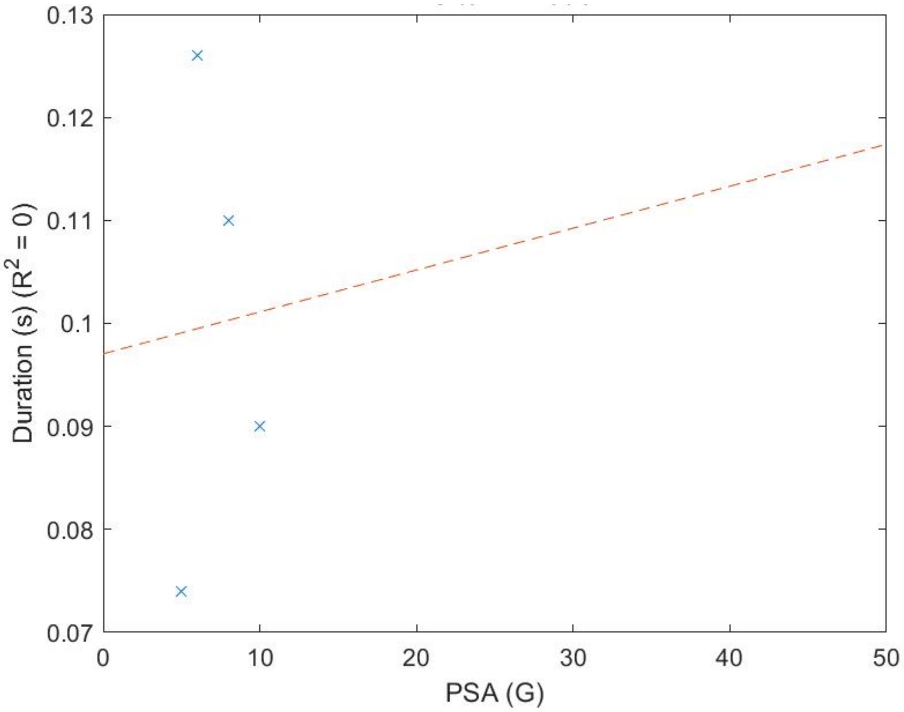


Figure C4. Linear regression duration model for oblique (-X+Y) front view impact direction. PSA is the peak sled acceleration.

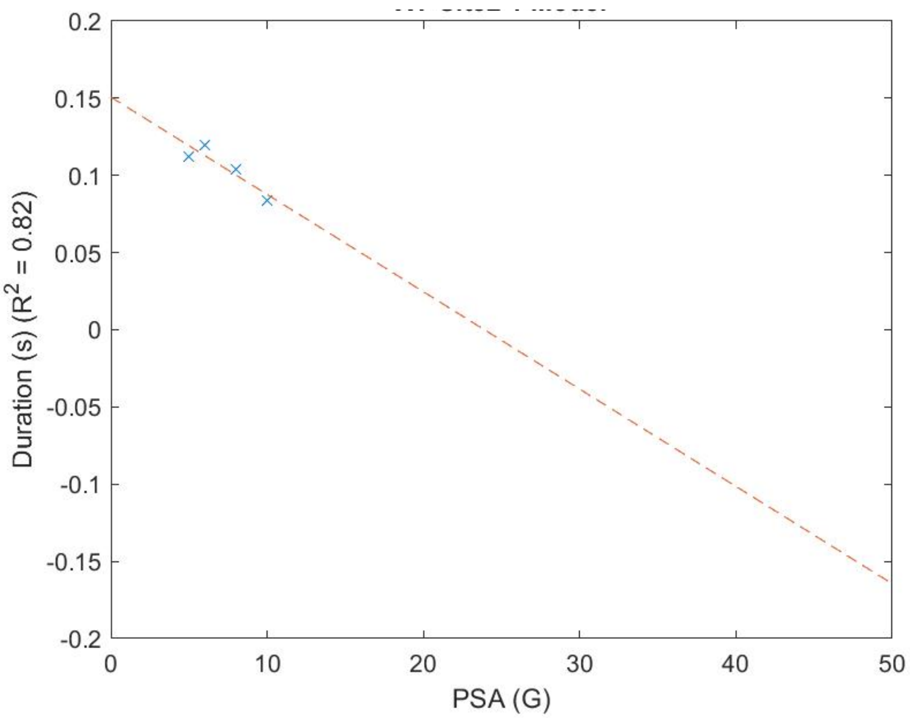


Figure C5. Linear regression duration model for oblique (-X+Y) side view impact direction.

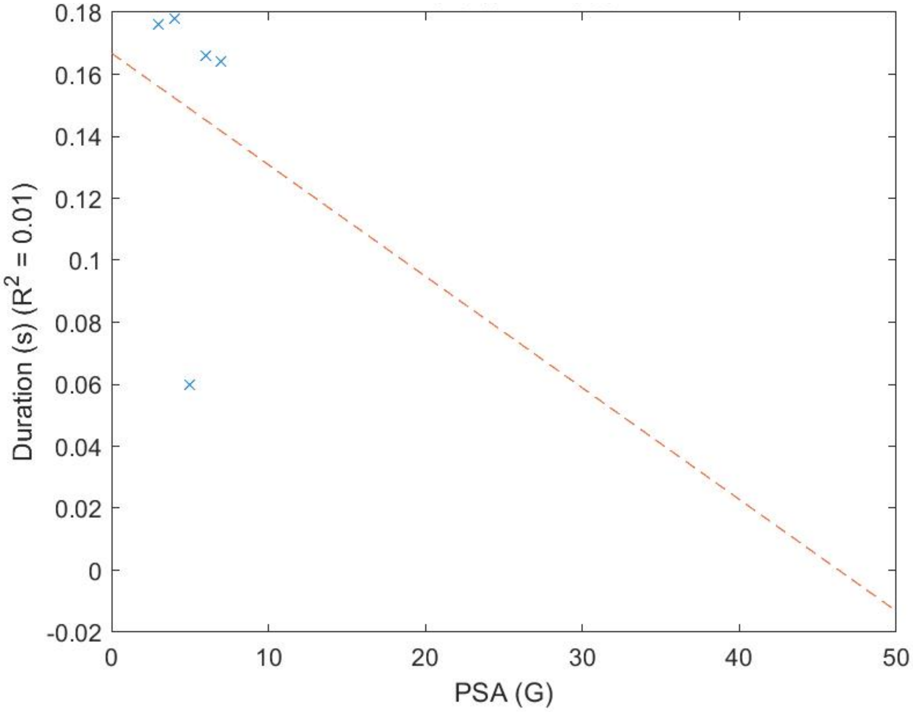


Figure C6. Linear regression duration model for off-axis (+Z-X10) impact direction.

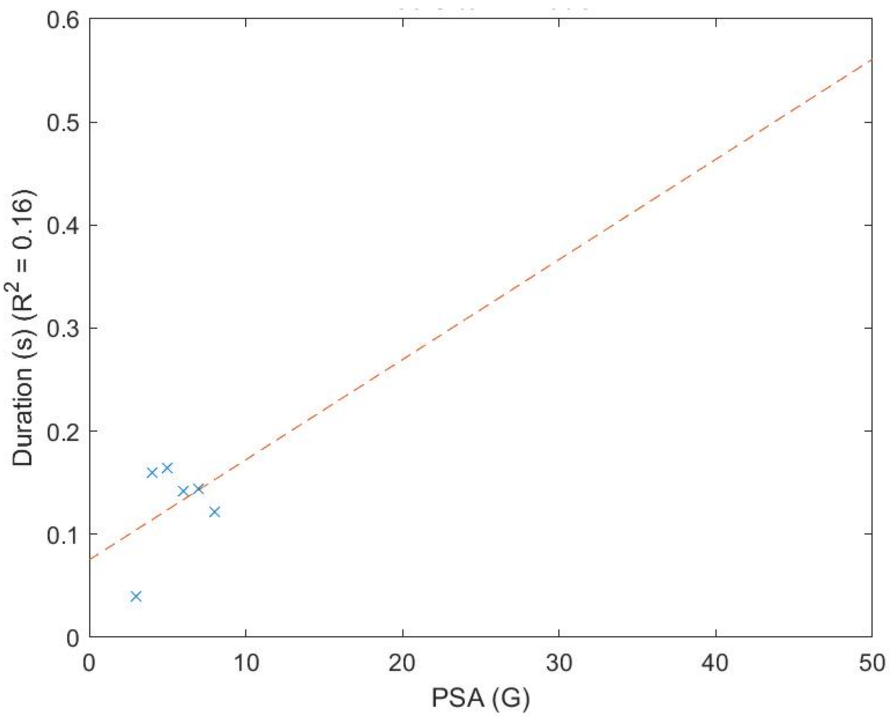


Figure C7. Linear regression duration model for off-axis (+Z-X30) impact direction.

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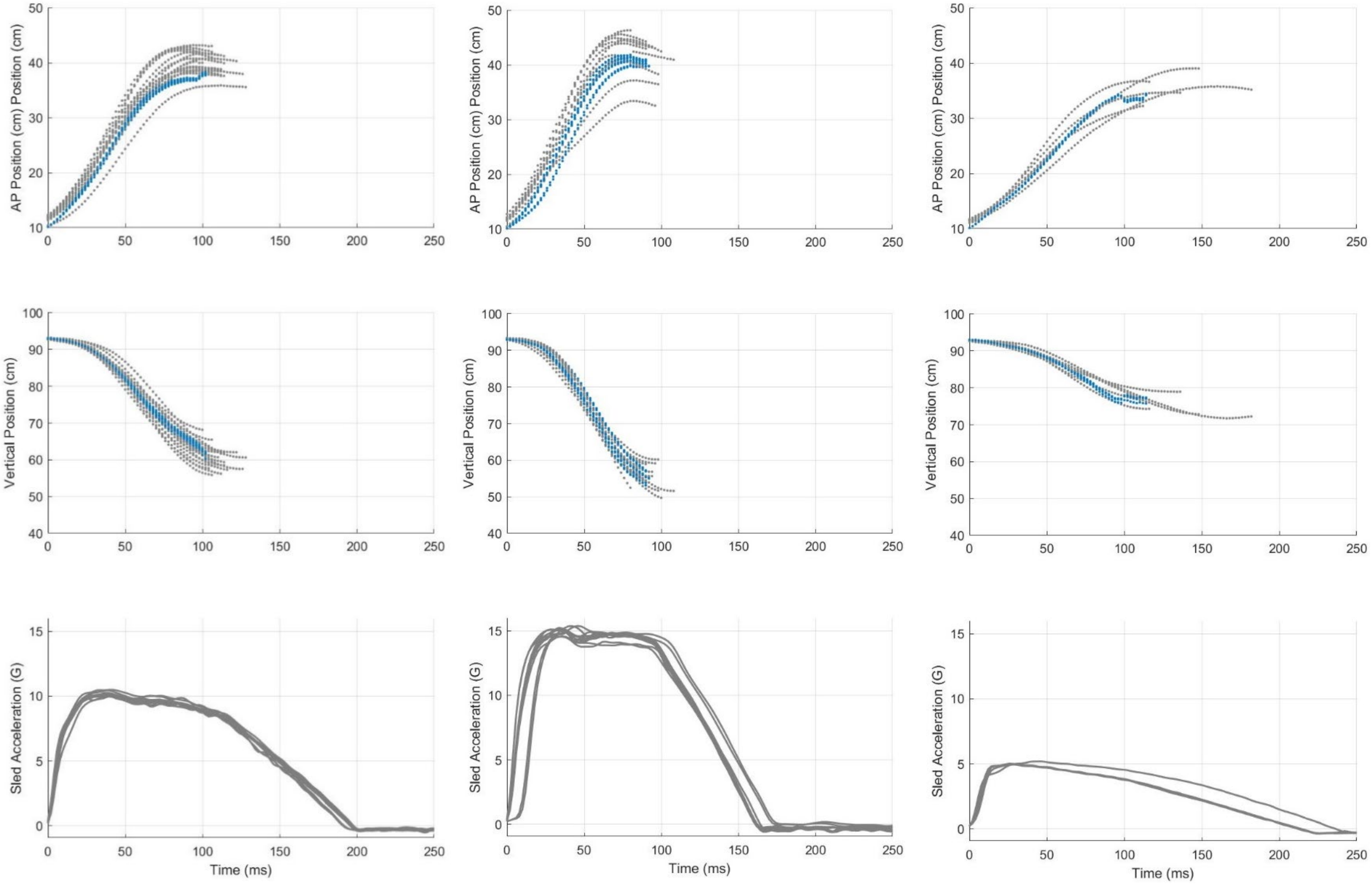
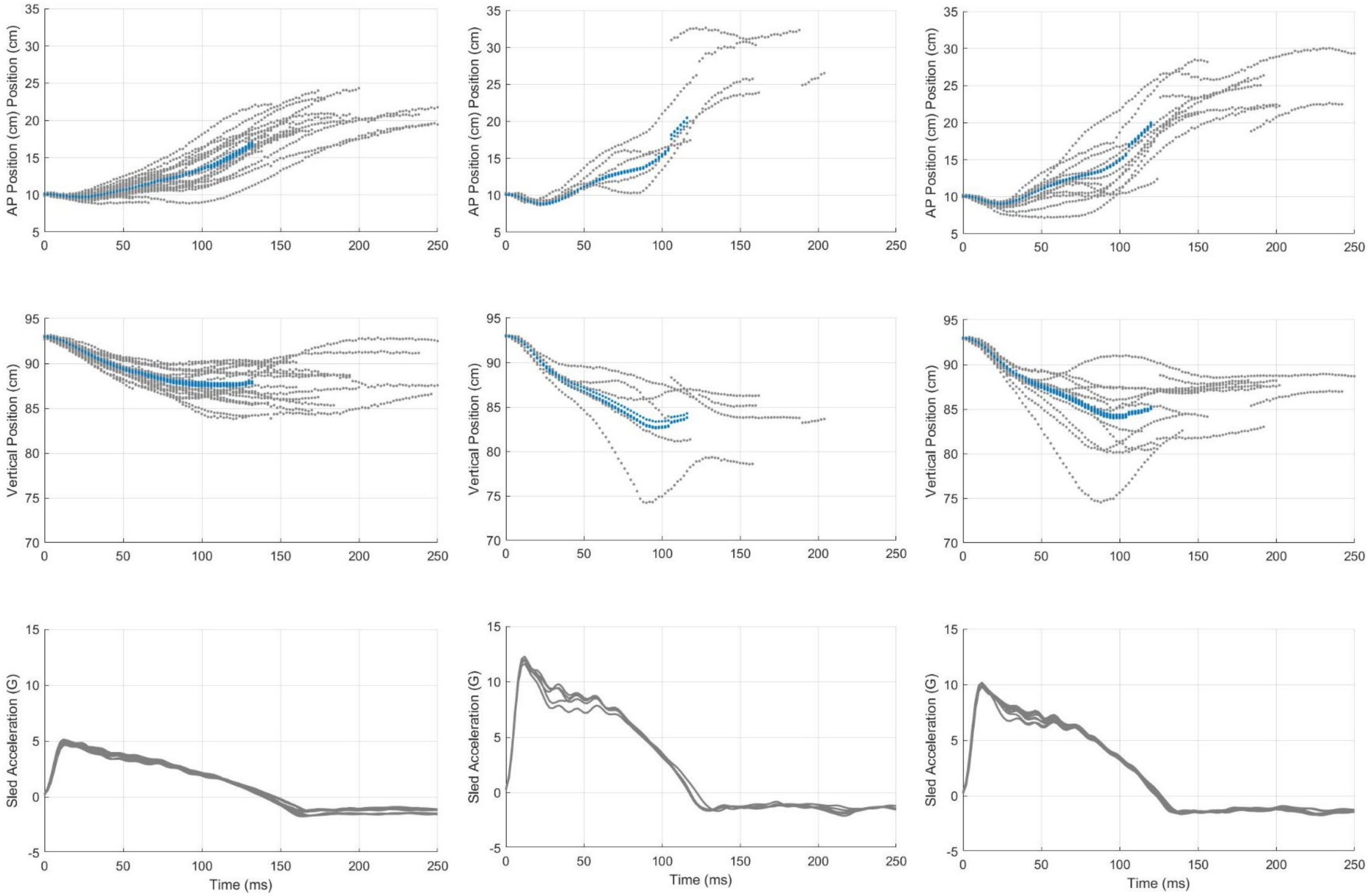
Appendix D. Comparison of Predicted and Experimental Response for Verification Tests



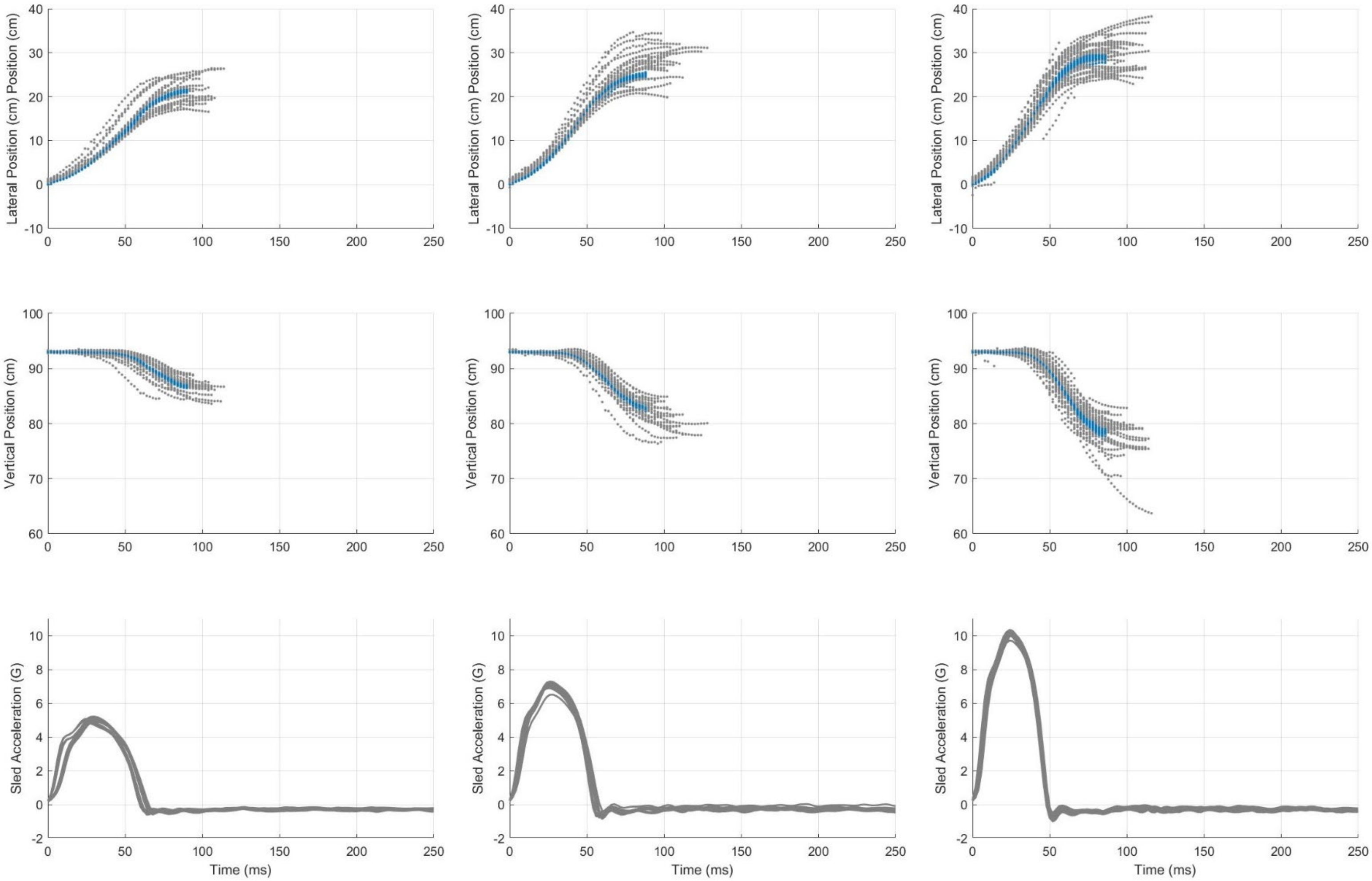
A B C

Figure D1. Time-based plots comparing predicted and experimental responses for frontal BDR HRV verification tests. Predicted and experimental responses are represented by the blue and gray markers, respectively. Plots have been grouped by peak sled acceleration to better show how the predicted responses fall within the family of HRV responses used to generate the response models for the 5 G (A), 10 G (B), and 15 G (C) frontal tests.



A B C

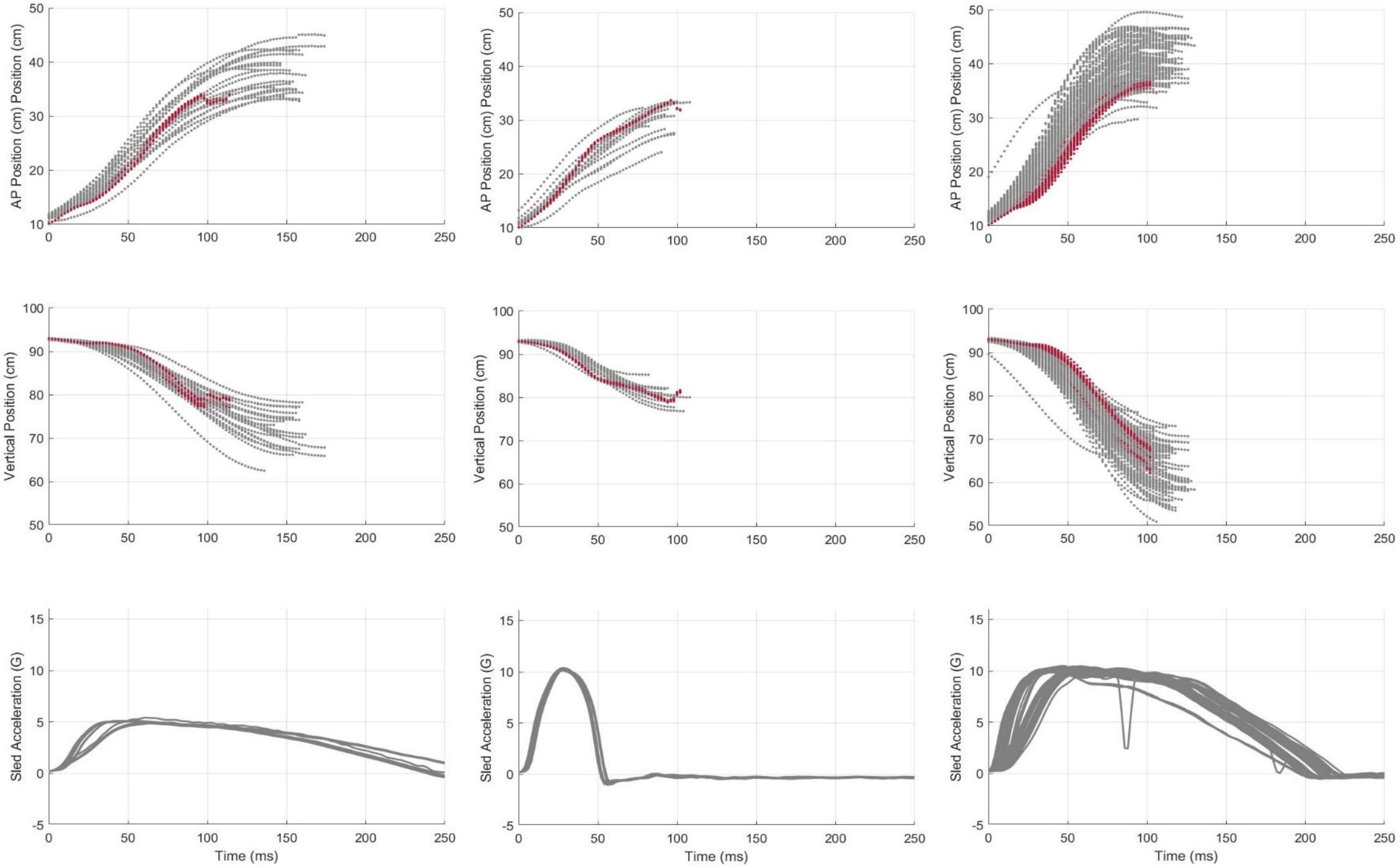
Figure D2. Time-based plots comparing predicted and experimental responses for axial BDR HRV verification tests. Predicted and experimental responses are represented by the blue and gray markers, respectively. Plots have been grouped by peak sled acceleration to better show how the predicted responses fall within the family of HRV responses used to generate the response models for the 5 G (A), 10 G (B), and 12 G (C) axial tests.



A B C

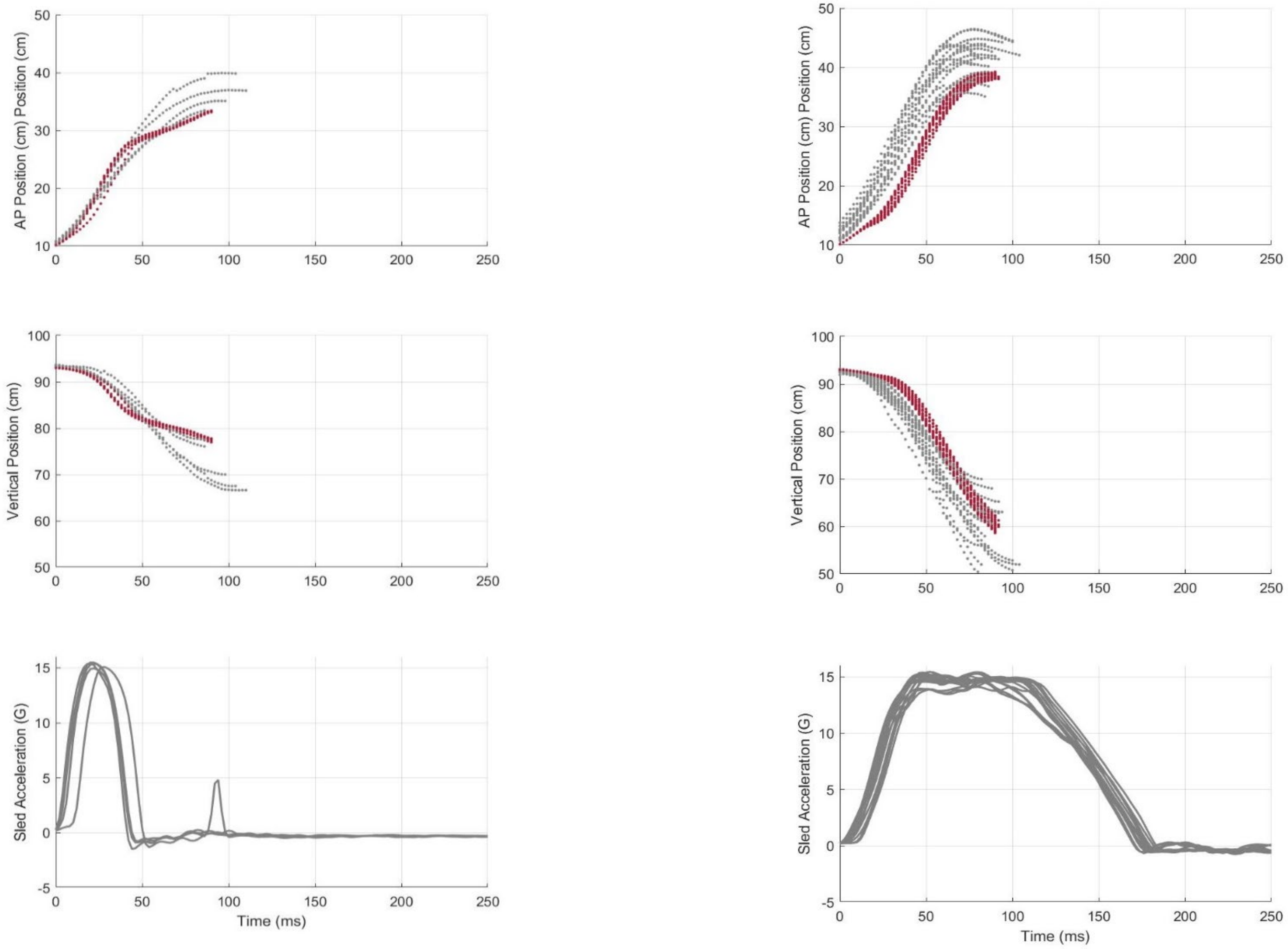
Figure D3. Time-based plots comparing predicted and experimental responses for lateral BDR HRV verification tests. Predicted and experimental responses are represented by the blue and gray markers, respectively. Plots have been grouped by peak sled acceleration to better show how the predicted responses fall within the family of HRV response used to generate the response models for the 5 G (A), 7 G (B), and 12 G (C) lateral tests.

Appendix E. Comparison of Predicted and Experimental Response for Validation Tests



A B C

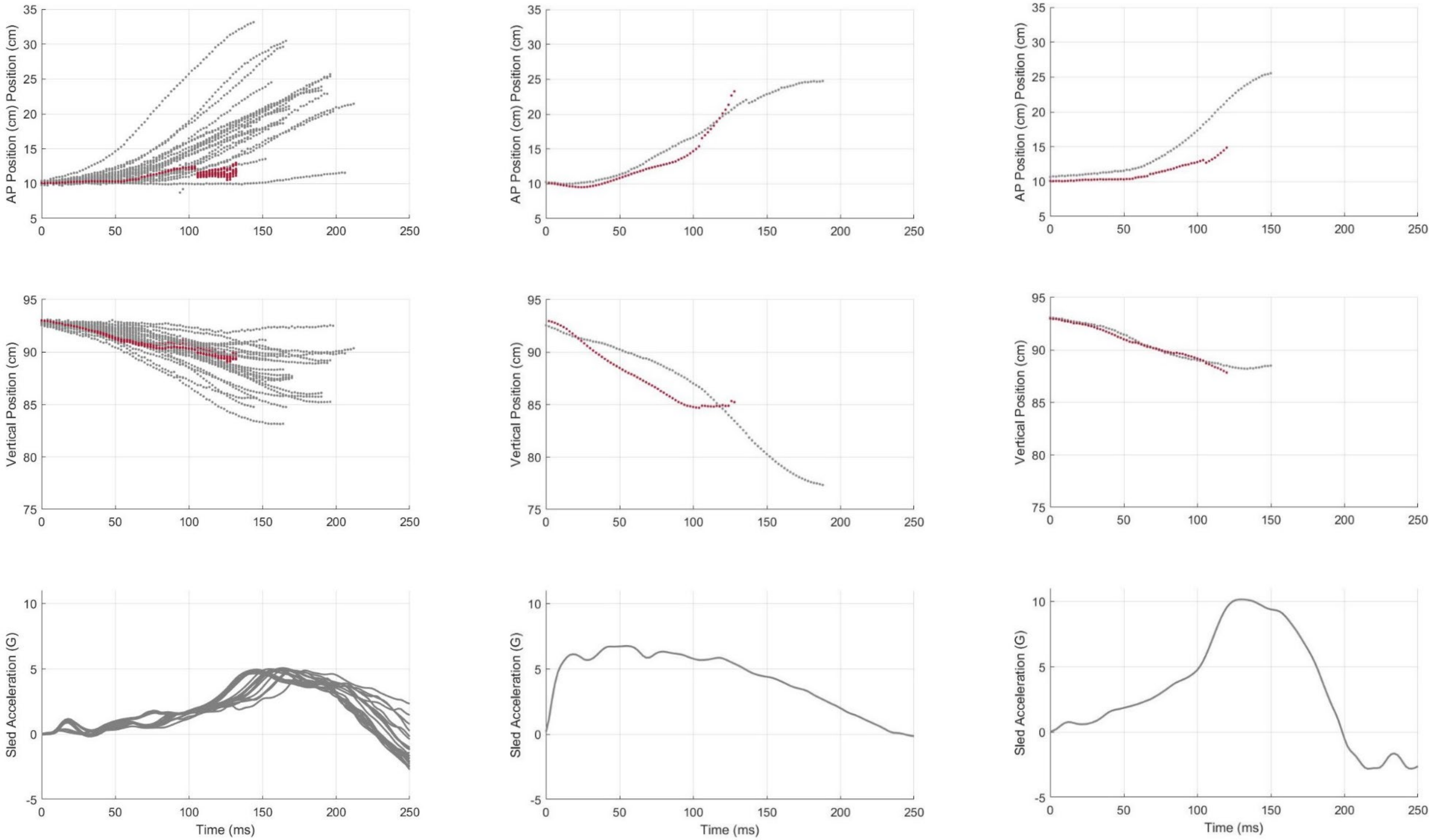
Figure E1. Time-based plots comparing predicted and experimental responses for frontal BDR HRV validation tests. Predicted and experimental responses are represented by the red and gray markers, respectively. Plots have been grouped by peak sled acceleration and, in some cases, peak sled velocity, to better show how the predicted responses fall within the family of HRV validation responses for the 5 G (A), 10 G (3 meters per second [m/s]) (B), and 10 G (14 m/s) (C) frontal tests.



A

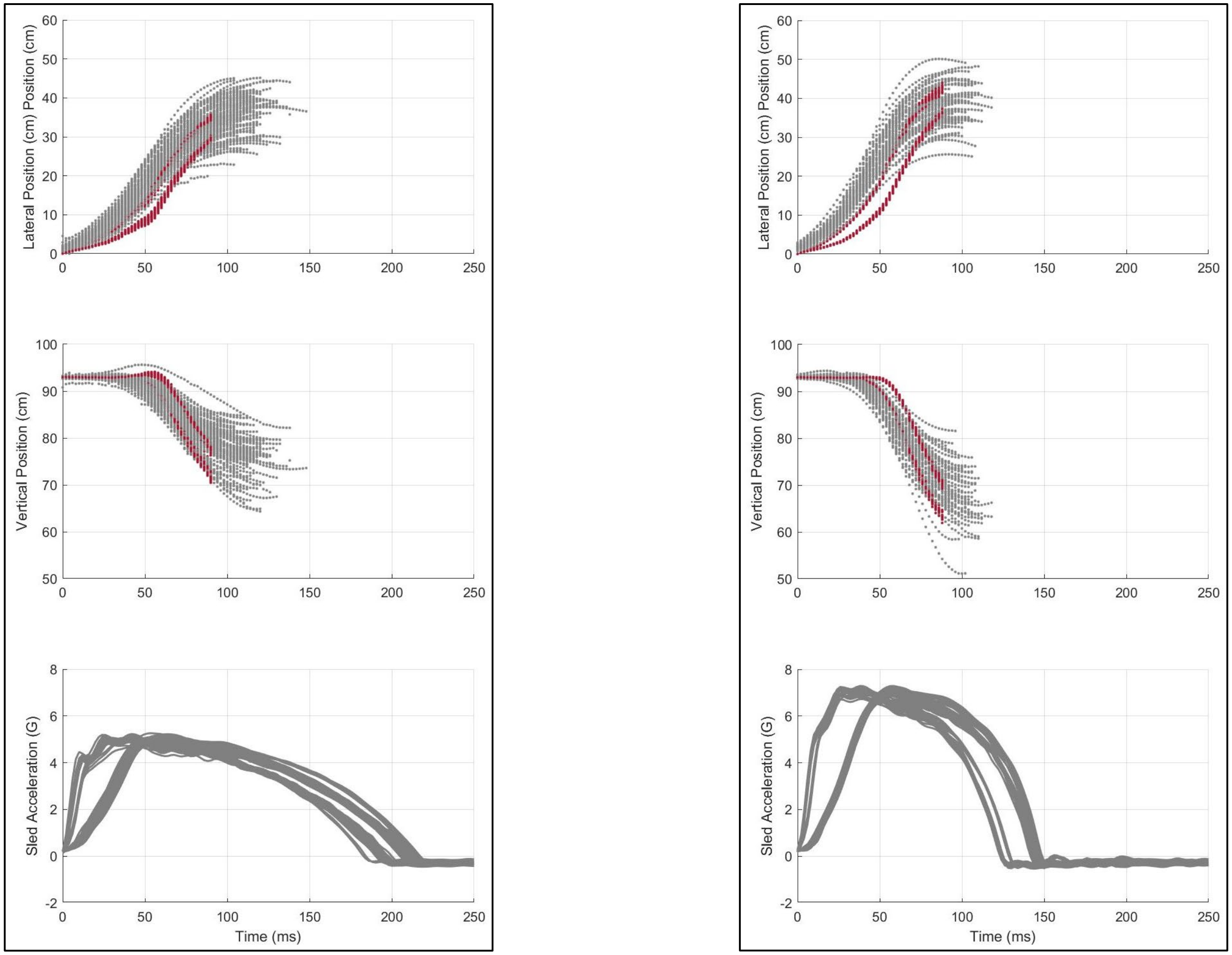
B

Figure E2. Time-based plots comparing predicted and experimental responses for frontal BDR HRV validation tests. Predicted and experimental responses are represented by the red and gray markers, respectively. Plots have been grouped by peak sled acceleration and peak sled velocity, to better show how the predicted responses fall within the family of HRV validation responses for the 15 G (4 m/s) (A) and 15 G (18 m/s) (B) frontal tests.



A B C

Figure E3. Time-based plots comparing predicted and experimental responses for axial BDR HRV validation tests. Predicted and experimental responses are represented by the red and gray markers, respectively. Plots have been grouped by peak sled acceleration and peak sled velocity, to better show how the predicted responses fall within the family of HRV validation for the 5 G (A) and 7 G (B), and 10 G (C) axial tests.



A B

Figure E4. Time-based plots comparing predicted and experimental responses for lateral BDR HRV validation tests. Predicted and experimental responses are represented by the red and gray markers, respectively. Plots have been grouped by peak sled acceleration and peak sled velocity, to better show how the predicted responses fall within the family of HRV validation responses for the 5 G (A) and 7 G (B) lateral tests.

Appendix F. Response Differences from Validation with BDR HRV Dataset

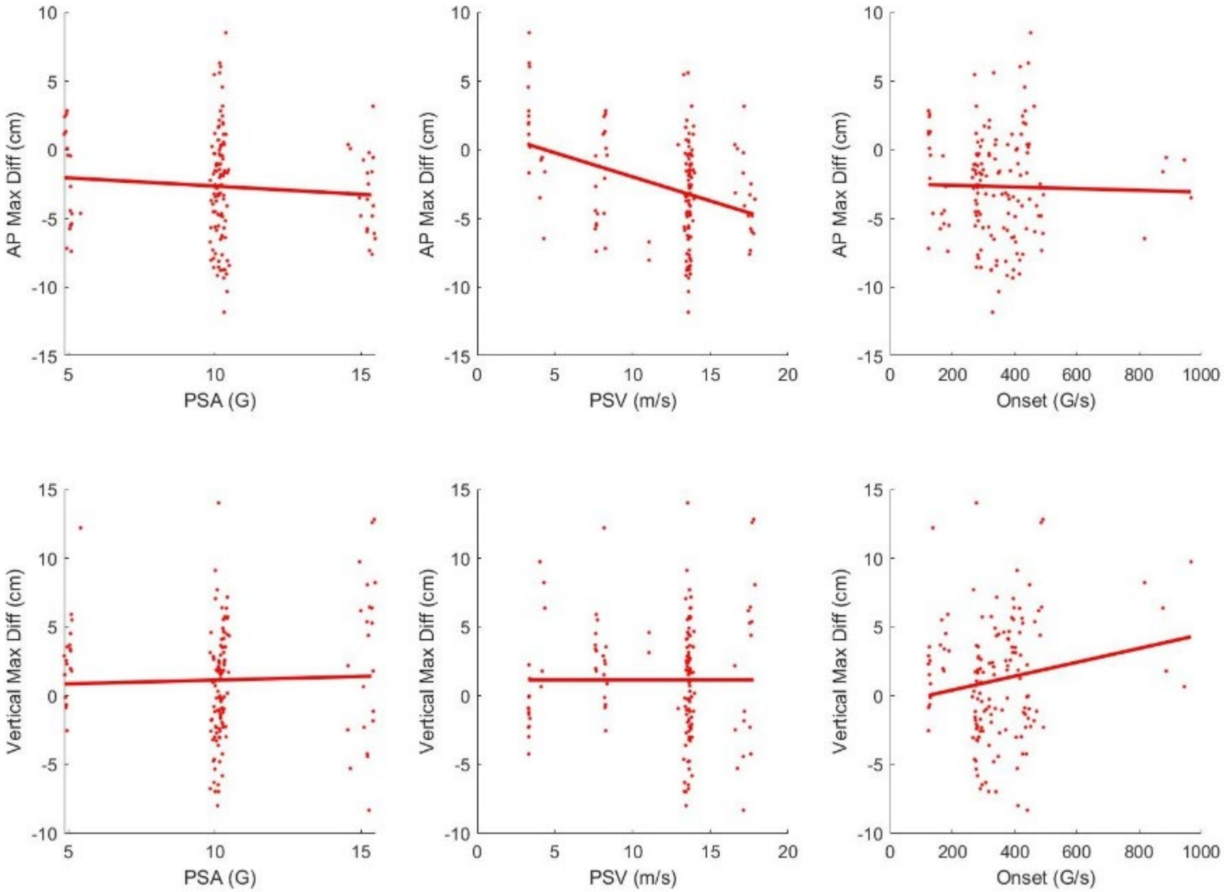


Figure F1. Differences in maximum anterior-posterior (AP) and vertical displacements for the frontal (-X) impact direction. Each point represents a test where the difference is calculated between the predicted and experimental maximum displacement.

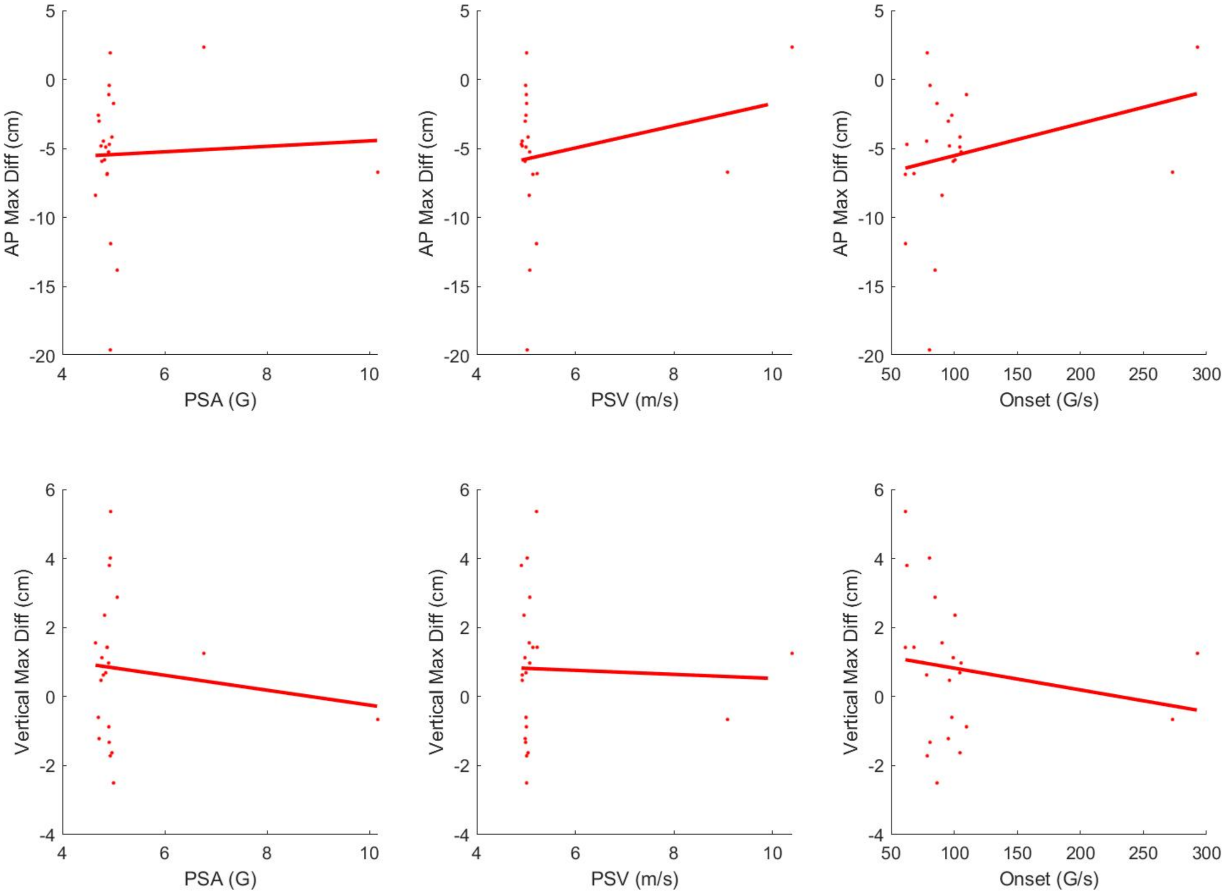


Figure F2. Differences in maximum anterior-posterior (AP) and vertical displacements for axial (+Z) impact direction. Each point represents a test where the difference is calculated between the predicted and experimental maximum displacement.

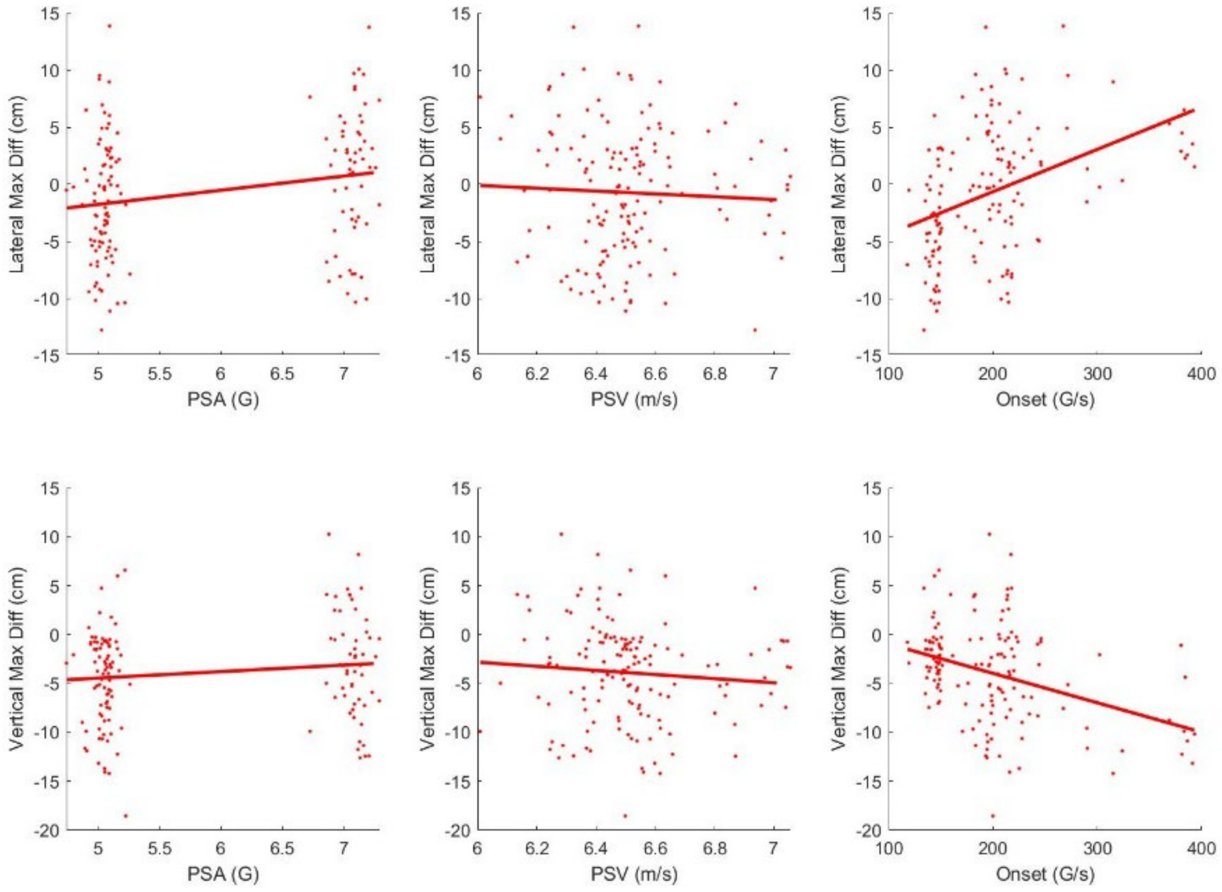


Figure F3. Differences in maximum lateral and vertical displacements for lateral (+Y) impact direction. Each point represents a test where the difference is calculated between the predicted and experimental maximum displacement.

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