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The Effects of Training and Subject Reproducibility during Vertical Impact Acceleration

Hilary L. Gallagher
Consortium Research Fellows Program

Joseph A. Pellettiere
Erica J. Doczy
Air Force Research Laboratory

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6. AUTHOR(S)
Hilary L. Gallagher (ORISE)
Joseph A. Pellettiere, Erica J. Doczy (AFRL/HEPA)

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14. ABSTRACT
To address questions regarding the effect of subject reproducibility and how it might affect data variability, a series of impact tests were conducted on the Vertical Deceleration Tower at AFRL/HEPA. Ten male and seven female subjects volunteered and were exposed to a combination of varying helmet weights and +Gz impact levels. Each combination was reproduced up to three times. The tests were first conducted in a sequential manner, with the lowest exposure experienced first for safety reasons. The last two replications were randomized so that the biodynamic response was not dependent on the last test configuration. Subjects were evaluated for reproducibility at 6, 8, and 10G with varying helmet weights. The head and sternum accelerations in the Z direction were used to analyze the biodynamic response along with neck loads generated at the occipital condyles. These neck forces were calculated using the helmet inertial properties, subject anthropometry, and the recorded head accelerations. The results from the study revealed no effect of training on the subjects' biodynamic response. A reproducibility limit was calculated for all subjects and all test conditions to be approximately 30% for the dependent variables. Results also showed a significant difference for gender on the neck force and a significant difference for both gender and experience for sternum Z acceleration. There was no meaningful correlation per test condition as a function of gender, experience, and reproduced exposures. This work was completed under the work unit: Neck Protection with Advanced Helmet and Vehicle Systems.

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Hilary Gallagher
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Joseph Pellettiere and Erica Doczy
Human Effectiveness Directorate, Air Force Research Laboratory
Wright-Patterson AFB, OH

ABSTRACT

Several studies have been conducted to collect and analyze the biodynamic response during vertical impact acceleration. There is little data, however, describing the effects of subject training on human response. There are also questions regarding the effect of subject reproducibility and how it might affect data variability. Research is required to determine the effect of training and to properly describe the human response to a vertical impact. This could potentially reduce musculoskeletal risks by providing proper bracing techniques for training implementation. A series of impact tests were conducted on the Vertical Deceleration Tower (VDT) at AFRL/HEPA. Ten male and seven female subjects volunteered and were exposed to a combination of varying helmet weights and +Gz impact levels: 6, 8, and 10 g. Each combination was reproduced up to three times. The tests were first conducted in a sequential manner, with the lowest exposure experienced first for safety reasons. The last two replications were randomized so that the biodynamic response was not dependent on the last test configuration. Seat pan, seat cushion, sternum, and head accelerations were collected using an on-board data acquisition system, and neck loads were calculated to compare the biodynamic responses using the varying weight. Electromyography was used to collect neck muscle response during bracing and on impact. Subjects were evaluated for reproducibility at 6, 8, and 10 +Gz with varying helmet weights. The head and sternum accelerations in the z-direction were used to analyze the biodynamic response along with neck loads generated at the occipital condyles (OC). These neck forces were calculated using the helmet inertial properties, subject anthropometry, and the recorded head accelerations. The results from the study revealed no effect of training on the subjects' biodynamic response. A reproducibility limit was calculated for all subjects and all test conditions to be approximately 30% for the dependent variables. Results also showed a significant difference for gender on neck force and a significant difference for both gender and experience for sternum Z acceleration. There was no meaningful correlation per test condition as a function of gender, experience, and reproduced exposures.

BACKGROUND

Many tests have been conducted to investigate the biodynamic response to vertical impact accelerations. The Vertical Deceleration Tower (VDT) is able to simulate vertical impact accelerations similar to those seen during an ejection or crash. It has been used in the past to investigate seats, cushions, helmet-mounted systems, and harnesses. Tests by Buhrman and Perry have been conducted on the VDT at Wright-Patterson Air Force Base

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to study the effects of vertical acceleration on biodynamic response [2, 5]. These studies have shown that subject training may be concurrent with testing. Previous tests have always been conducted in a sequential manner so that the order of severity increases for subject accommodation and safety.

There is little data on subject reproducibility and how it might affect data variability. Research is therefore required to determine the effects of subject training. Training has not always been thought to be beneficial; some studies show no obvious effects of training to reduce injury, while other studies show clear effects [4]. Biomechanical measures are sensitive indicators of training effects even though simplifications and assumptions are made in the process [4]. A study by Sovelius et al. concluded that during a training period for pilots facing +Gz accelerations there was no change in the maximal strength of the neck muscles. They were, however, able to see a decrease in muscle strain during +Gz loading for the cervical flexor and extensor muscles [7].

The objective of this study is to provide biodynamic response data to determine a subject's reproducibility of response during various vertical acceleration configurations and to determine the effect of subject training on data variability. Another objective of this study is to determine if there are statistically significant differences between the subject's biodynamic response per test condition as a function of gender, experience, and reproduced exposures. The results of this study will facilitate a reduction of pilot probability of injury in the event of an ejection by using proper position and brace training. The results may also provide a better understanding of the relationship between the potential of injury and bracing.

METHODS

A series of vertical impact acceleration tests have been performed on the VDT (Figure 1) at Wright-Patterson Air Force Base, OH. The VDT is comprised of a carriage-mounted seat, guided by two vertical rails, which is released to a free-fall state from a predetermined height that ranges from 5'8" to 11'7". The +Gz acceleration pulse is applied to the carriage when the plunger, mounted on the back of the carriage, is guided into the hydraulic decelerator between the two rails. When the water is displaced from the cylinder, the acceleration pulse is produced. The profile generated by the VDT is approximately a half-sine wave acceleration pulse with duration of 150 ms. Varying the drop height will change the peak G level reached during the deceleration pulse.

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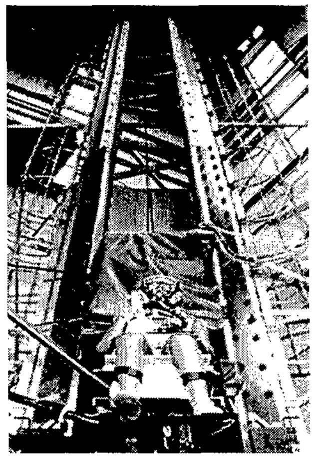

Figure 1: Vertical Deceleration Tower

This study was reviewed and approved for human testing by the Wright Site Institutional Review Board (IRB) at Wright-Patterson AFB, Ohio, USA and the US Air Force Surgeon General's Research Oversight Committee. Ten male and seven female subjects volunteered as members of the Wright Site Impact Acceleration Panel (IAP) at Wright-Patterson AFB, Ohio, USA and provided written informed consent before participating. All subjects were active-duty military and were medically qualified through the completion of a medical screening process. Anthropometric measurements were recorded for each subject, with the mean and range of age, weight, and height presented in Table 1.

Table 1: Subject age, weight, and height

	Males (n=10)	**Females** (n=7)
Age (yrs)		
Range	21-43	20-32
Mean	31.4 +/- 7.04	25.0 +/- 4.47
Weight (kg)		
Range	72.58-121.57	47.17-85.73
Mean	87.64 +/- 14.46	67.07+/-11.86
Height (cm)		
Range	175.26-195.58	157.48-178.08
Mean	181.48 +/- 5.5	168.41+/-9.06

The subjects were exposed to a combination of varying helmet weights and +Gz impact levels (Table 2). Each combination from the test matrix was reproduced up to three times for each subject. There was a minimum of one week between tests so that the biodynamic response was not affected by the previous test and to allow the subject to rest. The first tests were conducted as previously described in a sequential manner (A, B, C, D, E), with the order of severity increasing for subject accommodation and safety. The tests were then reproduced at least two more times in random order.

Table 2: Test Matrix

Impact Level	Total Head-Supported Weight		
	3.0 lb	4.0 lb	5.0 lb
6G	A		
8G	B		
10G	C	D	E

Before each test the subject was given consistent bracing and positioning instructions. The head with helmet was to be pushed against the headrest at all times with eyes looking forward. The subjects were told to keep their back and neck straight with their shoulders back and against the seat back. They were informed that after being raised to a predetermined height they would hear a count down from T10 to T0. At 2 seconds before drop time, the subjects were instructed to brace their helmet against the headrest and hold the brace throughout the drop and on impact. After being given instructions each volunteer was also asked to produce three maximum voluntary contractions (MVC) of the neck muscles before each test. The subject was seated in an upright position with feet placed on a wheeled platform (to reduce the use of leg muscles). They were instructed to brace their head against a headrest, concentrating only on their neck muscles. The instructions were to exert a maximum force contraction against the fixed headrest. The MVC was shown on a continuous visual feedback screen in front of them at eye level. The subjects were verbally encouraged to produce their MVC. The maximum force of the three contractions was taken. The MVC is used to normalize the electromyography (EMG) data to address variability.

After the MVC was collected the subjects were then positioned in the VDT carriage with the headrest and backrest parallel to the vertical rails. The generic seat was designed to duplicate the contours of the seat back and seat pan of the operational ACES II ejection seat. The subjects were restrained using a PCU-15/P or a PCU-16/P restraint harness and lap belt. All restraint points were pre-loaded to 20 +/- 5 lbs. Subjects were fitted with a Variable Weighted Impact helmet (VWI), which consisted of a modified HGU-55/P flight helmet to allow for adjustable weight and center-of-gravity (Cg). Identical weights of various sizes were placed on each side of the helmet to maintain symmetry. For this study the total helmet weights were 3.0, 4.0, and 5.0 lbs. with the Cg location being similar to that of currently used Air Force helmet-mounted systems (frontally loaded). An MBU-12/P oxygen mask was used in conjunction with an Integrated Chin Nape Strap (ICNS) equipped helmet during the tests (Figure 2).

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Figure 2: Male Subject Prior to Impact Test on Vertical Deceleration Tower

Data were collected by an on-board data acquisition system. The subject was instrumented with accelerometers and surface EMG sensors. The chest pack included an angular rate sensor and a z-axis accelerometer, and the bite bar included a tri-axial accelerometer and angular accelerometer. The biodynamic response was monitored by collecting the seat pan, seat cushion, sternum, and head accelerations. Neck muscle activity was recorded from the right and left sternocleidomastoid and upper trapezius muscles using surface EMG. The skin was cleaned with alcohol before the placement of the sensors, and the reference sensor was placed on C7 of the spinous process

RESULTS

Data were collected from 17 subjects for a total of 128 vertical deceleration impact tests. Ten of the subjects (5 male, 5 female) had no impact acceleration test experience, while 7 subjects (5 male, 2 female) had some prior experience. Head and sternum Z accelerations were collected and neck forces were calculated (Table 3).

Table 3: +Gz, Helmet Weight, and Descriptive Statistics for Each Cell for All Subjects and Replications

		Helmet		Sternum Z Acceleration			Head Z Acceleration			Neck Force Z (lb)		
Cell	Gz	Weight (lb)	N	Min	Median	Max	Min	Median	Max	Min	Median	Max
A	6	3	23	6.8	8.5	11.7	7.0	8.3	14.0	87.1	101.8	120.7
B	8	3	36	10.6	12.6	20.3	10.4	12.2	17.9	120.5	143.3	217.3
C	10	3	30	15.1	16.8	23.5	11.4	16.1	20.6	121.1	180.5	234.2
D	10	4	26	13.6	17.8	20.3	12.0	15.3	19.8	160.9	190.2	248.2
E	10	5	13	14.8	17.8	26.1	13.0	15.5	20.5	183.7	212.9	285.7

An in-house neck load program computes the neck forces based on the measured head linear and angular accelerations, and the inertial properties of the helmet and head. The program estimates the head weight and moments of inertia based on the subject's head circumference and body weight. The neck force is calculated at the occipital condyles for each subject using the equations of motion for a rigid body (Figures 3 and 4). The linear acceleration at the center of mass of the combined head/helmet system is computed from the measured linear and angular accelerations at the bite bar. The subjects are sorted by experience and then again by gender. The replications are labeled 1, 2, and 3 and the circled replications distinguish those subjects who had a flexion or extension of the neck upon impact. These figures also show the data variability of each subject for cell C (10G, 3.0-lb helmet, Figure 3) and D (10G, 4.0-lb helmet, Figure 4).

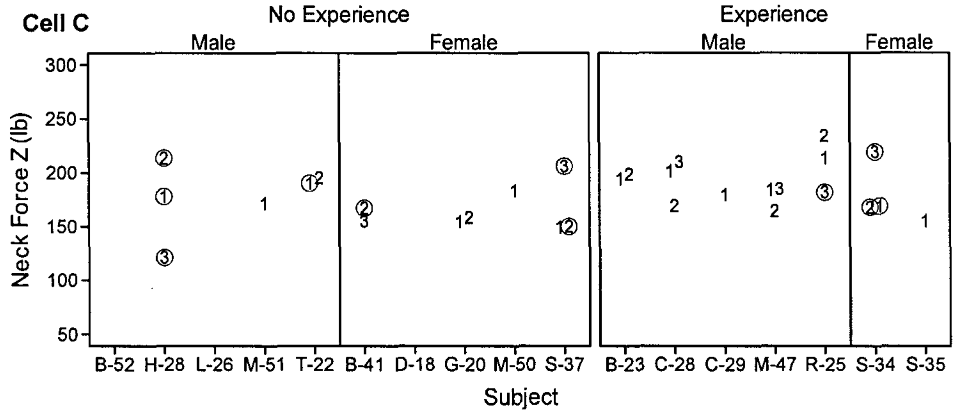

Figure 3: Calculated Neck Force for Each Subject Testing Cell C

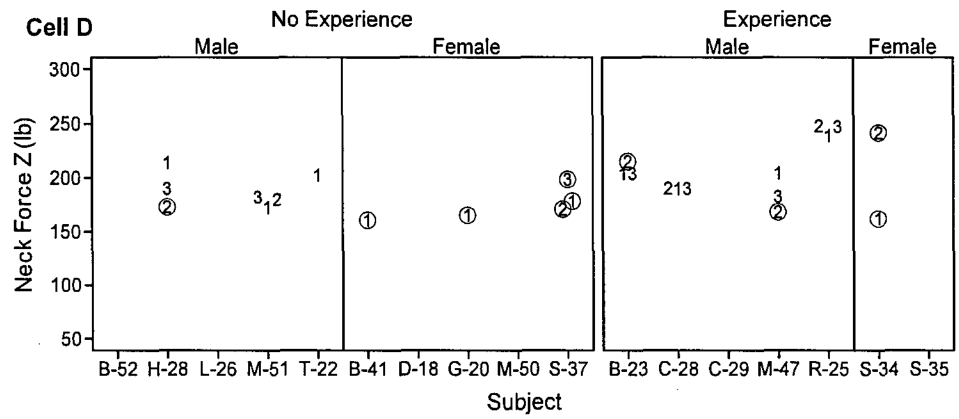

Figure 4: Calculated Neck Force for Each Subject Testing Cell D

Factors of interest in analyzing the acceleration and force data (dependent variables) include replication (i.e., order effect), flexion/extension, cell, experience, and gender. As seen in the figures above, there are many instances where a subject is missing an entire cell or does not have three replications for a cell. Also, there are many instances where a subject has neck flexion/extension for all of the replications or none of the replications for a particular cell, indicating that some subjects may be more prone to neck motion. Visual inspection of plots indicates no meaningful relationship between flexion/extension and any of the dependent variables: therefore, this factor was not considered further.

There were two models used in analyses of variance (ANOVA). The first model helped determine whether replication had an effect and whether a replication effect varies with experience. The second model helped determine whether cell, experience, or gender had an effect. Since there was a low number of subjects and most subjects had missing data, it was decided to treat subject as a fixed factor. These analyses should be interpreted cautiously; conclusions should not be generalized to a subject population, but should be considered as a "best guess" for these subjects only.

For the first model, all combinations of subject and cell where the subject had three replications were used. Dependent variables were then averaged across cells for each combination of subject and replication. There were 6 subjects with experience and 5 subjects with no experience. Factors used were experience, replication, and subject with subject nested in experience. The error term used for all F-tests was the replication*subject (experience) interaction. Among all 3 dependent variables there was not a replication main effect ($p > 0.1781$) or a replication*experience interaction ($p > 0.7373$). The second model used the following factors: cell, experience, gender, and subject with subject nested in experience and gender. Cell E was not included in the analyses since the only data in this cell were from one male with no experience and four males with experience. Due to missing data in at least 2 cells from B, C, and D, subjects B-52, L-26, and D-18 were not used. Since there were a low number of subjects for each combination of experience and gender, it was decided to include only main effects and two-way interactions in the model (Table 4).

Table 4: Results from Analyses of Variance

Dependent Variable	Source	df	SS	F	*p*
Sternum Z Acceleration	Cell	3	923.38	133.93	0.0001
	Experience	1	9.97	4.34	0.0403
	Gender	1	14.92	6.49	0.0126
	Subject (Experience*Gender)	10	113.73	4.95	0.0001
	Cell*Experience	3	0.63	0.09	0.9642
	Cell*Gender	3	2.24	0.32	0.8075
	Experience*Gender	1	4.08	1.78	0.1862
	Error	85	195.34		
	Total	107	1480.80		
Head Z Acceleration	Cell	3	639.01	89.04	0.0001
	Experience	1	1.48	0.62	0.4344
	Gender	1	2.47	1.03	0.3121
	Subject (Experience*Gender)	10	51.60	2.16	0.0283
	Cell*Experience	3	6.05	0.84	0.4741
	Cell*Gender	3	5.97	0.83	0.4799
	Experience*Gender	1	0.25	0.10	0.7476
	Error	85	203.34		
	Total	107	1030.52		
Neck Force Z (lb)	Cell	3	79198.29	72.10	0.0001
	Experience	1	1279.46	3.49	0.0650
	Gender	1	2210.92	6.04	0.0160
	Subject (Experience*Gender)	10	12106.60	3.31	0.0012
	Cell*Experience	3	1440.49	1.31	0.2760
	Cell*Gender	3	163.06	0.15	0.9304
	Experience*Gender	1	108.27	0.30	0.5880
	Error	85	31121.39		
	Total	107	158650.72		

(**df** = degrees of freedom, **SS** = Sum of Squares, **F** = F-test, ***p*** = probability)

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Test results indicate no significant interactions. The cell main effect was significant for all three dependent variables. A Bonferroni paired comparison procedure was used to compare the cell means with a family-wise error level of 0.05. For all three dependent variables, cells A, B, C, D were all significantly different from each other, with the exception of cells C and D. There was a significant main effect of experience for sternum Z acceleration and a significant main effect of gender for sternum Z acceleration and neck force Z. Least Squares Means were determined from the analyses of variance. These means use parameter estimates to determine estimated means (Table 5 and Figure 5).

Table 5: Least Squares Means from the Analyses of Variance

Factor	Level	Sternum Z Acceleration	Head Z Acceleration	Neck Force Z (lbs)
Cell	A	9.2	8.7	105
	B	12.9	12.3	148
	C	17.5	15.8	178
	D	17.3	15.7	191
Experience	No	13.9	13.0	152
	Yes	14.6	13.3	160
Gender	Male	13.8	13.0	161
	Female	14.7	13.3	150

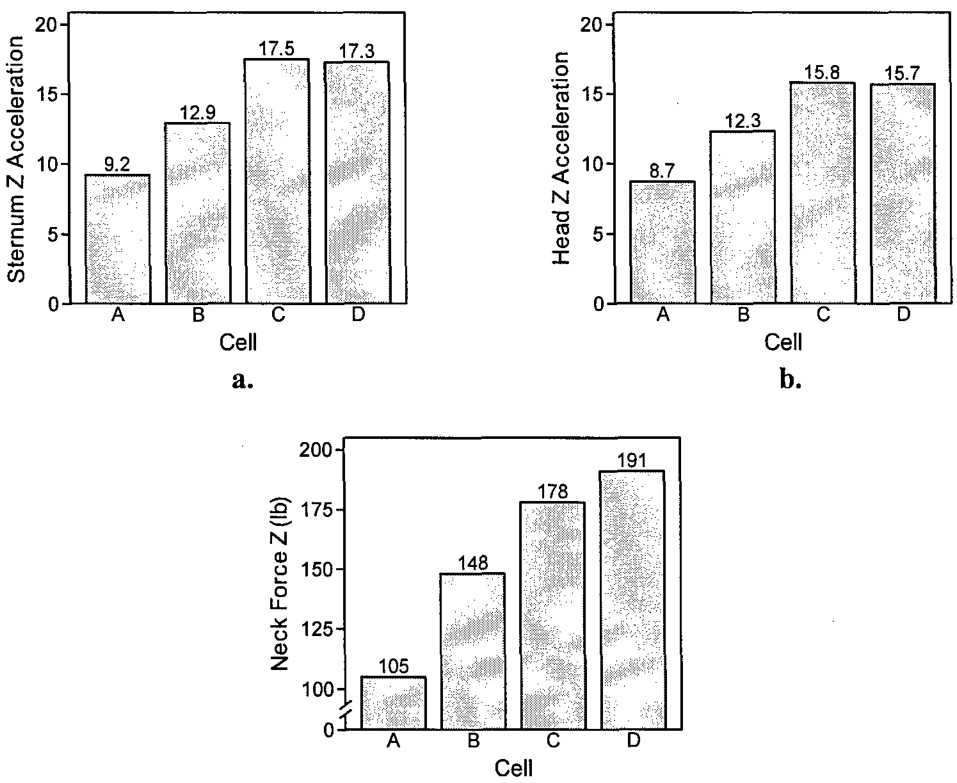

Figure 5: Least Square Means from the Analyses of Variance
a. Sternum Z Acceleration b. Head Z Acceleration c. Neck Force

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For cell E, means were determined across replications for the 5 subjects with data. These means were then averaged across subjects (sternum Z acceleration mean = 18.8, head Z acceleration mean = 16.2, neck force Z mean = 223). These cell E means are not comparable to those in Figure 5 since they come from a subset of the subjects.

A reproducibility limit (RL) can be defined as: approximately 95% of all pairs of replications from the same subject and cell (generated on different weeks) should differ in absolute value by less than the RL. Each combination of subject and cell that had at least two replications was used to determine the RL (Table 6). Due to the low sample size, a RL was not determined for each cell separately; however, the figures indicate that the variability of replications is similar across all cells. The RL was calculated by pooling the variance of replications and then multiplying the square root of this variance by 2.77. The mean was calculated by averaging across replications for each subject and cell used to determine the RL and then averaging these means across subject and cell. The procedure for determining the reproducibility limit is described in the American Society of Testing Materials (ASTM) designation: E 691-92 [1].

Table 6: Reproducibility Limits (RL) for Each Dependent Variable

Dependent Variable	Mean	RL	RL % of Mean
Sternum Z Acceleration	15.1	4.7	31
Head Z Acceleration	13.9	4.7	34
Neck Force Z (lb)	168.0	56.8	34

DISCUSSION

The second modeled ANOVA test revealed a significant main effect of gender for neck force. As shown in Table 5 there is lower head acceleration for males than for females, but the neck force for the males is higher. This may not be a meaningful correlation because of how the neck force was calculated. Statistically, the body weight of males compared to females is significantly higher using a t-test ($t = 0.0074$). The subjects' body weight was used in a regression equation to estimate the head weight. Therefore, if the body weight increases so do the estimated head weights, calculating a larger neck force.

There is also a significant main effect of experience and gender for the sternum Z acceleration. Many factors could have influenced this effect including: different body masses and proportions, seat cushion compression, and a change in the support strap system. Mid way through this study, the support strap system was changed because the old system was allowing for too much motion for the smaller subjects, many of whom were female. A further investigation will have to be conducted to analyze the differences between the old system and the new system. This could add a new variable into the study.

The results of this study also revealed a high reproducibility limit. This RL could have been a result of uncontrollable factors such as: length of time between test days, personal training, motivation, a change in position, different bracing technique, environmental factors, and natural body variations (weight, health). A data set created from a study done by Buhrman in 1999 contained 2-4 replications from each of 47 subjects for neck force Z of cell C (10G, 3.0-lb helmet). The RL from these data was 41.6 with RL % of mean = 22. The difference in RL % of mean between the current data and the 1999 data is somewhat due to a few subjects in the current data having a relatively large range for his/her replications (example: subject H-28 in Figure 3). Considering results from both data sets, one could conclude that, in general, two replications of neck force Z from the same subject and cell, generated on different weeks, could differ by as much as 25-30%.

CONCLUSION

In conclusion, we did not see that training had an effect on the subjects' biodynamic response during vertical impact accelerations. Also the reproducibility limit was higher during this study when compared to the study mentioned above. In general, two replications for the same subject and cell, generated on different weeks, could differ by as much as 25-30% for neck force Z. Further testing would have to be done with a larger number of subjects and with subjects completing all replications for a stronger conclusion to be reached on subject training and reproducibility. Future testing on the VDT should continue to test in a sequential manner since there were no signs of an advantage to testing in a randomized manner. This will also secure the subjects' safety. We also found no meaningful correlations per test condition for gender, experience, repeated exposures or neck flexion/extension.

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BIOGRAPHIES

Hilary Gallagher is a biomedical engineer for the Consortium Research Fellows Program. She has a BS in Biomedical Engineering from Wright State University and is currently pursuing a MS in Human Factors Engineering. Her research has centered on collecting EMG data from human subjects during impact events and measuring test data reproducibility.

Joseph Pellettiere is the Technical Advisor and mechanical engineer for the Biomechanics Branch, Human Effectiveness Directorate, Air Force Research Laboratory. He has a BS in Biomedical Engineering and an MS in Mechanical Engineering from Case Western Reserve University, and a Ph.D. in Mechanical Engineering from the University of Virginia. His experience is in biomechanics, human simulation and injury, crash protection and prevention using both testing and computational technologies. He currently leads several projects in the branch including modeling and simulation, seat system interfaces and neck injury protection.

Erica Doczy is a biomedical engineer for the Biomechanics Branch, Human Effectiveness Directorate, Air Force Research Laboratory. She has a BS in Biomedical Engineering from Wright State University and is currently pursuing an MS in Biomedical Engineering. Her experience is in impact biomechanics and human systems test and evaluation. She is currently the associate investigator of a study examining the effects of helmet weight during vertical impacts using manikin and human volunteer subjects.

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