AFRL-RH-WP-TR-2020-0057

QUANTIFYING PATIENT VIBRATION PATTERNS DURING AMBULANCE BUS (AMBUS) GROUND TRANSPORT

Suzanne D. Smith PhD
Consultant, Infoscitex

Christopher J. Dooley
David S. Burch, PhD
711 HPW/RHB

July 2020
Interim Report

DISTRIBUTION A. Approved for public release.

AIR FORCE RESEARCH LABORATORY
711TH HUMAN PERFORMANCE WING,
AIRMAN SYSTEMS DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

NOTICE AND SIGNATURE PAGE

AFRL-RH-WP-TR-2020-0057 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

__//signature//____________________
DONALD L. HARVILLE
Work Unit Monitor
Biomedical Impact of Flight Branch

__//signature//___________________
DAVID BURCH, PhD
Core Research Area Lead
Biomedical Impact of Flight Branch
Airman Biosciences Division

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*: 01-07-2020

2. REPORT TYPE: Interim

3. DATES COVERED *(From - To)*: November 2017 – April 2020

4. TITLE AND SUBTITLE
Quantifying Patient Vibration Patterns During Ambulance Bus (AMBUS) Ground Transport

5a. CONTRACT NUMBER: FA8650-14-D-6500-0001

5b. GRANT NUMBER:

5c. PROGRAM ELEMENT NUMBER: 62202F

5d. PROJECT NUMBER: 5329

5e. TASK NUMBER: 08

5f. WORK UNIT NUMBER: H0GW (53290812)

6. AUTHOR(S)
*Suzanne D. Smith
**Christopher J. Dooley, David S. Burch

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Infoscitex, a DCS Corp.

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
**Air Force Materiel Command
Air Force Research Laboratory
711th Human Performance Wing
Airman Systems Directorate
Airman Biosciences Division
Biomedical Impact of Flight Branch
Wright-Patterson AFB, OH 45433

10. SPONSOR/MONITOR'S ACRONYM(S): 711 HPW/RHBF

11. SPONSOR/MONITOR'S REPORT NUMBER(S): AFRL-RH-WP-TR-2020-0057

12. DISTRIBUTION / AVAILABILITY STATEMENT
DISTRIBUTION A. Approved for public release.

13. SUPPLEMENTARY NOTES 88ABW-2020-2686 , cleared 26 August 2020

14. ABSTRACT Dynamic motion and vibration can affect patient comfort, disease and injury management, and health outcomes during military emergency evacuation. This study sought to characterize and assess the low frequency vibration exposures encountered by the supine litter patient during AMBUS ground transport. The AMBUS test route was a modification of the AE personnel training route used at Wright-Patterson AFB OH. Three volunteers participated as supine litter patients during six test runs. Litter locations included the mid and aft bus sections, left and right sides, and two vertical tiers. Three runs were conducted with both the unbraced and braced litter using trained AE personnel. Three portable battery-powered data acquisition units (DAUs) were used to collect triaxial accelerations at the litter/patient back and pelvis interfaces, and at the patient head, chest, and leg. A substantial vertical (X) peak was observed at all measurement sites between 3 and 4 Hz, with smaller peaks occurring in the horizontal directions. This peak was statistically higher at the aft bus section (paired t-test, P<0.5). Minimal differences were observed in the accelerations between the left and right sides, and tier 2 and tier 3. Bracing was shown to reduce the vibration at both bus sections, but differences were variable and small. Comfort reactions associated with the point Vibration Total Value (*pVTV*) ranged primarily between "fairly uncomfortable" and "very uncomfortable" at both the mid and aft bus sections. It is emphasized that the ISO 2631-1 only provides guidance on evaluating comfort of healthy supine individuals at the pelvis interface. The low frequency vibration exposures measured in this study, and the associated ISO Comfort Reactions, strongly suggest that the injured supine patient will experience significant discomfort and pain during AMBUS ground transport. While it is expected that the patient will be appropriately sedated to minimize discomfort and pain during transport, the low frequency motions encountered by the patient early in the evacuation process could lead to compromised health outcomes, particularly with regard to head and spine injuries. It is imperative that strategies be implemented that can appropriately minimize these motions.

15. SUBJECT TERMS **Human Vibration, Military En-Route Care, Military Emergency Evacuation**

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Donald Harville
Unclassified	Unclassified	Unclassified	SAR	36	19b. TELEPHONE NUMBER *(include area code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

The Air Force Research Laboratory (AFRL), 711 Human Performance Wing thanks the USAF School of Aerospace Medicine Expeditionary Education and Training Department (USAFSAM/ETT), located at Wright-Patterson AFB (WPAFB) OH, for their support of this project.

1.0 SUMMARY

The overall purpose of this flight test program is to collect engineering data for characterizing exposure of patients to vibration during all stages of military aeromedical evacuation (AE), including both ground and air vehicle transport. The data will be used to conduct a comfort assessment of the exposures in accordance with existing standards. The data will also be used to identify specific issues regarding the litter system and seats that may significantly affect the transmission of vibration and motion and exacerbate patient condition. This particular study focused on litter patient vibration during ground transport aboard the ambulance bus (AMBUS).

This test program supports the need for information to help en route patient care meet future challenges as cutting-edge treatments are introduced to support the wounded during combat and disasters. The study aligns with AFMA Strategic Objectives A1, E3, and E6, and will help bridge the gaps identified by the 2014 AFMS DCR 1 (Surgery during long-range transport), Research Knowledge (32, Pain management for patients with low back pain), and AMC's gap 11 (related to AFMS Research Knowledge gaps 1-5 and 20) regarding the cumulative effects of the stressors of flight. The study is being funded by the Joint Program 6/Combat Casualty Car Research Program (JPC-6/CCCRP) Joint En Route Care (J-ERC) Award solicited for the Defense Health Agency, Research, Development, and Acquisition (DHA RDA) Directorate.

The AMBUS test route was a modification of the AE personnel training route used at Wright-Patterson AFB OH. Three volunteers participated as supine litter patients during six test runs. Litters were mounted within the AMBUS following standard protocols. Locations included the mid and aft bus sections, left and right sides, and two vertical tiers. Three runs were conducted with the unbraced litter, and three runs were conducted with the litter motion braced by trained AE personnel. Three portable battery-powered data acquisition units (DAUs) were used to collect triaxial accelerations at the litter/patient back and pelvis interfaces, and at the patient head, chest, and leg. Twenty-second data records were collected at each of 25 targeted route locations. The acceleration spectra were estimated for all sensor sites and directions. The overall weighted accelerations were used to calculate the point vibration total value (*pVTV*) for assessing comfort reaction (ISO 2631-1: 1997).

A substantial vertical (X) peak was observed at all measurement sites between 3 and 4 Hz, with smaller peaks occurring in the horizontal directions. This peak was statistically higher at the aft bus section (paired t-test, $P<0.5$). Additional horizontal peaks were also observed between 10 and 20 Hz that were more prevalent at the mid bus section. Minimal differences were observed in the overall unweighted accelerations between the left and right sides, and vertical tier 2 and tier 3. Bracing was shown to significantly reduce the overall vibration at both the mid and aft bus sections, but the results depended on the test run. Most differences were relatively small. For those route locations where the back horizontal (Y) vibration was highest, the braced condition produced notably higher motions. Comfort reactions associated with the *pVTV*s ranged primarily between "fairly uncomfortable" and "very uncomfortable" at both the mid and aft bus sections. The weighted vertical accelerations were the major contributors to the discomfort associated with the *pVTV*s at the pelvis and back interfaces, while the weighted head accelerations in both the vertical and horizontal directions contributed to the higher discomfort

associated with the head *pVTV*s. It is emphasized that the ISO 2631-1 only provides guidance on evaluating comfort of healthy supine individuals at the pelvis interface.

The methods and procedures established in this study will set the precedent for future operational and research activity related to AE and en route care with regard to vibration and motion encountered during patient transport aboard both military and civilian air and ground vehicles. The data gathered during this study can be used to re-create the patient/interface vibration in the laboratory for studying specific biodynamic, physiological, and psychological effects in a controlled environment, developing and evaluating mitigation strategies and equipment design options, and establishing appropriate standards and criteria for assessing patient exposures to transport vibration.

2.0 INTRODUCTION

Dynamic motion and vibration can affect patient comfort, disease and injury management, and health outcomes during military medical evacuations. In particular, dynamic motion and vibration during ground transport aboard the AMBUS have been associated not only with patient pain, but medical equipment failure. Unlike transport aboard military aircraft, where the vibration tends to be higher in frequency and associated with the propulsion system, ground transport exposes occupants primarily to lower frequency vibration in the range where humans are most sensitive and which can cause relatively high levels of motion being transmitted to the injured person. In addition, transport aboard a ground vehicle may well be the first method of evacuation encountered by the injured on their way to a treatment facility.

Two studies have been completed by the Air Force Research Laboratory (AFRL) 711 Human Performance Wing (HPW) onboard military emergency evacuation aircraft; one study targeted the C-130H (Smith S. D. et al. 2019), the second study targeted the C-130J. As with medical transport aboard aircraft, the first step is to clearly characterize the actual human multi-axis vibration exposure aboard the AMBUS. The data are used to identify the frequency components, acceleration magnitudes, and direction of the vibration entering the recumbent or semi-supine occupant at the patient/litter interface, and to characterize the vibration transmitted to major patient body parts (such as the head, chest, and leg). Current vibration exposure guidelines and standards recommend the measurement of vibration at the interfaces between the supporting surface and the occupant. For the recumbent (or semi-supine) occupant, these interfaces include the pelvis, back, and head (ISO 2631-1: 1997 and ISO 2631-1: 1997/Amd. 1: 2010). Guidance on the assessment of comfort and perception is provided for all postures including the seated, standing, and recumbent or semi-supine occupant. However, guidance on the assessment of health risk is currently limited to the seated posture due to the lack of health effects data for other postures.

The specific objectives of this study are:

1. Collect multi-axis acceleration data to characterize the supine patient/litter vibration during transport aboard the AMBUS.
2. Assess the vibration exposures at the patient/litter interfaces in accordance with existing human vibration guidelines and standards to estimate patient comfort and perception levels and to gauge potential health outcomes.
3. Document data in the Collaborative Biomechanics Data Network (CBDN) for use by researchers, equipment designers, and health care providers

3.0 METHODS AND PROCEDURES

3.1 Overview

The AMBUS used for collecting data was located at the USAF School of Aerospace Medicine Expeditionary Education and Training Department (USAFSAM/ETT), located at Wright-Patterson AFB (WPAFB) OH (Figure 1). Litters can be mounted to the left and right side walls

Figure 1. AMBUS

in the forward, mid, and aft sections of the bus. At each section, there are three vertical tiers available for mounting litters. For this study, litters were located on both the left and right side, in the middle and aft sections, at tier 2 (middle tier). In addition, one subject was located on the right side, aft section, tier 3 (highest tier). The USAFSAM/ETT provides training to the ETTs using the AMBUS and a test course defined for travel around Area B, WPAFB. The test course was slightly modified for the study and took approximately 20 minutes to complete. Twenty-five locations along the course were targeted for data collection during each test run. Three volunteers participated in each test run. A total of six test runs were conducted. During each test run, data were collected for the three occupied litter locations. Three of the test runs were conducted without bracing of the litter. Three test runs were conducted with bracing by trained AE personnel. Bracing included pushing against the side of the litter to minimize litter motion when encountering rough road. The litter located in the aft section on the top tier was not braced. The test matrix for each test run are defined in Table 1. The test matrix was configured so that each subject occupied three different litter locations for comparison. For example, tests runs were conducted with Subjects 1 and 2 occupying both the left mid tier 2 and left aft tier 2 for comparing the mid and aft bus sections. In addition, Subjects 1 and 2 also occupied the right tier 2 for comparing left vs right side. Subject 3 occupied both tier 2 and 3 on the right side aft section, and tier 2 on the left side of the aft section.

Table 1. Test Matrix

Subject	Run #	Left or Right Side	Bus Section	Tier Level/ Seat	Bracing
1	1	Left	Middle	Tier 2	N
	2	Left	Middle	Tier 2	Y
	3	Left	Aft	Tier 2	N
	4	Left	Aft	Tier 2	Y
	5	Right	Aft	Tier 2	N
	6	Right	Aft	Tier2	Y
2	1	Left	Aft	Tier 2	N
	2	Left	Aft	Tier 2	Y
	3	Left	Middle	Tier 2	N
	4	Left	Middle	Tier 2	Y
	5	Right	Middle	Tier 2	N
	6	Right	Middle	Tier 2	Y
3	1	Right	Aft	Tier 2	N
	2	Right	Aft	Tier 2	N
	3	Right	Aft	Tier 3	N
	4	Right	Aft	Tier 3	N
	5	Left	Aft	Tier 2	N
	6	Left	Aft	Tier 2	N

3.2 Equipment, Instrumentation, and Measurement Sites

Three Remote Vibration Environment Recorders (REVERs), developed by the AFRL Human Effectiveness Directorate (711 HPW/RH), were used to collect multi-axis vibration data during each AMBUS test run through the course. Each REVER included the following components (Figure 2):

1. A 16-channel data acquisition unit (DAU)
2. Two battery packs (Large and Small)
3. Triaxial accelerometer packs
4. Triaxial acceleration pads
5. One trigger device
7. Connection/extension cables as required

Specifications for the REVER components, including dimensions and weights, are listed in the Appendix, Table A-1. The 16-channel DAU enclosure is fabricated using Delrin and 606-T6 aluminum and provides electromagnetic interference (EMI) shielding (EME Corporation, Arnold, MD). The small battery pack is rated at 12 volts/2.7 amp-hours. The battery will operate for approximately 2.7 hours. The larger battery pack is rated at 12 volts/4.0 amp-hours and can operation for approximately 4 hours. Each triaxial accelerometer pack includes three orthogonally-arranged miniature accelerometers (Entran EGAX-25, Entran Devices, Inc., Fairfield, NJ) embedded in a Delrin® cylinder. Double-sided adhesive tape or mounting tape is used to secure the pack to the appropriate sites. The triaxial acceleration pad is a flat rubber disk

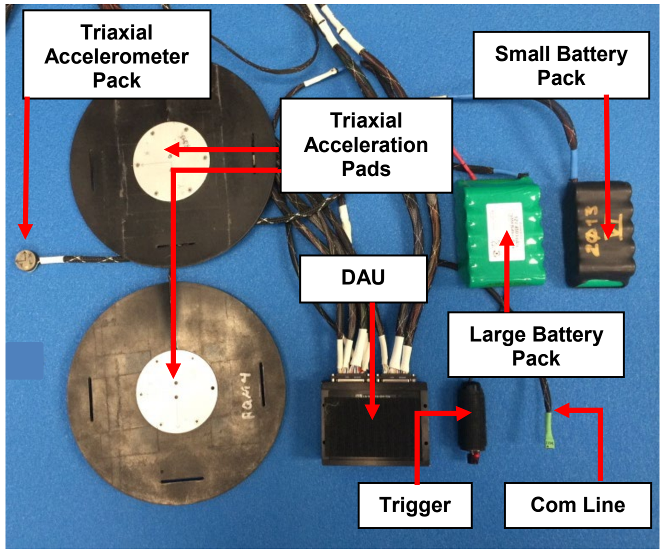

Figure 2. REVER Components.

that includes an embedded triaxial accelerometer pack. The pads are secured to occupant interface surfaces using double-side adhesive tape and duct tape. The triaxial acceleration pads were used for measuring the vibration transmitted to the occupant via the litter in accordance with ISO 2631-1: 1997. The triggering device was used to initiate the data collection.

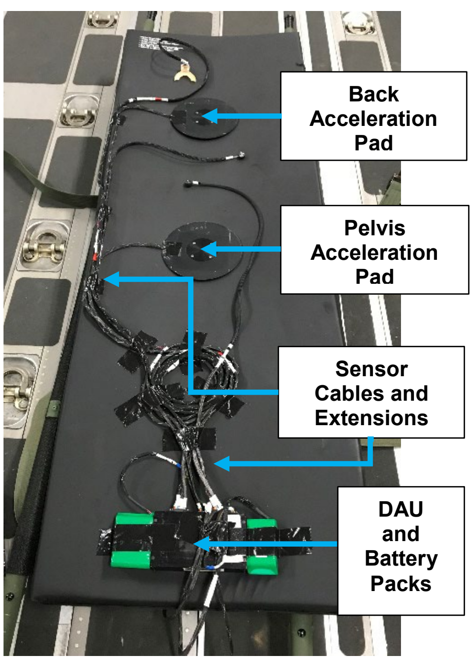

Figure 3. DAU and batteries, back and pelvis acceleration pads attached to litter.

One REVER system (PicoDas DAU, Table A-1) was required for measuring the vibration for each supine (recumbent) patient/litter configuration. Instrumentation of the litter and patient were similar to that used during previous flight tests (Smith et al., 2019). The DAU and battery packs were attached to the litter between the participant's feet and secured with duct tape (Figures 3 and 4).

Triaxial acceleration pads were attached to the litter surface using double-sided adhesive tape at the interfaces between the participant's back and pelvis (Figure 3). A triaxial pack was attached to a bitebar (Figure 5) using double-sided adhesive tape for measuring head translation. A triaxial pack was directly attached to the participant's chest using double-side adhesive tape (Figure 6). A triaxial accelerometer pack was also attached to the participant's leg using

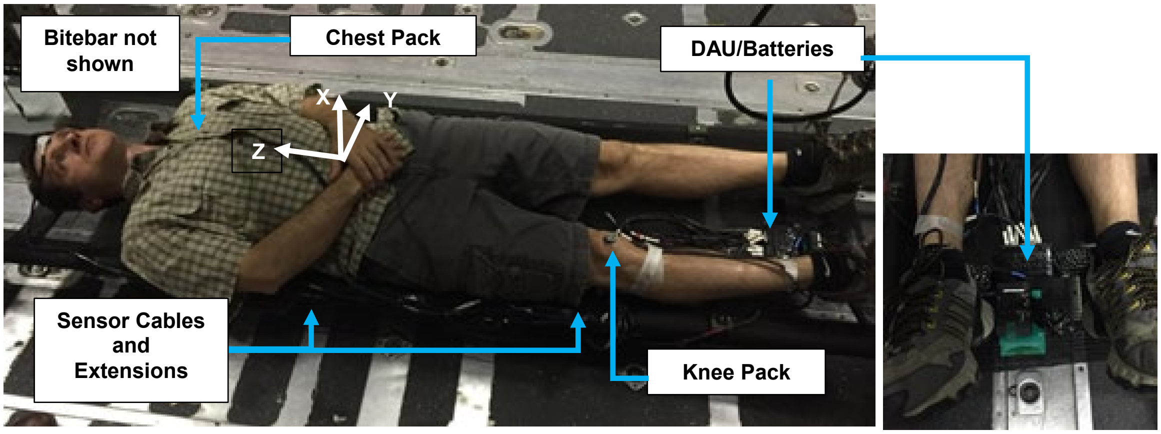

Figure 4. Patient/litter configuration.

Figure 5. Bitebar with accelerometer pack.

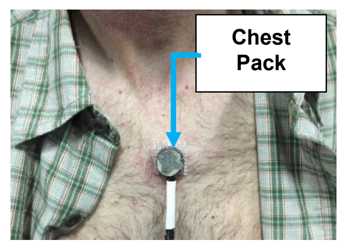

Figure 6. Chest accelerometer pack.

double-sided adhesive tape (Figure 4). Packs attached to the body were further secured with medical tape, as necessary. Cables from the bitebar pack, chest pack, back pad, and pelvis pad were secured to the side of the litter using duct tape (Figure 3). Extension cables were used to connect cables from the packs and pads to the DAUs as necessary. All cables were routed and secured to avoid any discomfort and hazard to the participants and test support personnel, particularly in the case of an emergency egress. The participant was restrained using a chest strap and leg strap.

A laptop computer system was used for initial calibrations and setup of the instrumentation, and to arm the system prior to the test run. Specific sensors for each measurement site and direction were assigned to a specific channel in the DAU. Once armed, the computer was disconnected from the DAU and stowed during the test run. A triggering device (Fig. 2) was used to initiate data collection from each of the three DAUs. Upon completion of the test run, the laptop was reconnected to each DAU and all channels downloaded for subsequent processing.

3.2 Data Collection, Processing, and Analysis

3.2.1 Data Collection.

During each test run, acceleration data were collected at each of the three patient locations, for each measurement site, at each of the targeted test course locations. A trigger cable from each of the three DAUs was routed to the test conductor responsible for data collection at all three locations. Once triggered, the DAU would collect data for a pre-specified amount of time. Once triggered, data were automatically collected for 20 seconds, filtered at 250 Hz, and digitized at 1024 samples per second. Twenty-five to 27 data records were collected during each test run.

3.2.2 Data Processing and Analysis.

A computer program developed by AFRL 711 HPW/RH was used to separate the 20-second records for each channel and assemble all channels for a particular record into a table of time histories. For each record, the time histories were processed using the MATLAB® Signal Processing Toolbox (The MathWorks, Inc., Natick, MA) to estimate the constant bandwidth spectral content. Using Welch's Method (Welch, P. D., 1967), each 20-second time history was divided into two-second sub-segments with a 50% overlap. A Hamming window was applied to each sub-segment and the resultant power spectral densities averaged over the 20-second period. The root-mean-square (rms) acceleration, a_{rms}, was calculated from the power spectral densities in 0.5 Hz intervals. The constant bandwidth rms acceleration spectra were used to locate and compare the peak accelerations and associated frequencies.

Each acceleration time history was also processed in one-third octave proportional frequency bands using a software program developed for MATLAB® (Couvreur, 1997). The accelerations were reported at the center frequency of each respective one-third octave band. The one-third octave data were used to calculate the overall unweighted and weighted rms accelerations. The overall unweighted acceleration level, a_{uw}, between 1 and 80 Hz was calculated at each patient location for all measurement sites:

$$a_{uw} = \left[\sum_i a_{rmsi}^2\right]^{1/2} \tag{1}$$

where a_{rmsi} is the rms acceleration associated with the *ith* frequency component (in 0.5 Hz increments for constant bandwidth analysis, and at the center frequency of the one-third octave band for proportional bandwidth analysis).

The assessment of discomfort (comfort reaction) for the supine (recumbent) patient followed the guidelines in ISO 2631-1: 1997 and the MIL-STD 1472G, 2012, using the frequency weightings and multiplying factors listed in Table 2. Note that the X direction of the body (spine-chest) is in the vertical direction relative to the vehicle, while the Z direction is in the longitudinal or long axis of the supine body (feet-head). Figure 4 includes the basicentric coordinate system for the supine (recumbent) occupant (ISO 2631-1:1997).

The overall weighted rms acceleration level, a_w, was calculated between 1 and 80 Hz in each axis (X, Y, and Z) relative to the coordinate system defined for the recumbent occupants:

Table 2. ISO 2631 Frequency Weightings and Multiplying Factors (ISO 2631-1: 1997)

RECUMBENT POSTURE				
COMFORT REACTION				
	Pelvis		Head	
Direction	Frequency Weighting	Multiply Factor	Frequency Weighting	Multiply Factor
X (Vertical)	W_k	$k = 1.0$	W_j	$k = 1.0$
Y (Lateral)	W_d	$k = 1.0$	W_d	$k = 1.0$
Z (Longitudinal)	W_d	$k = 1.0$	W_d	$k = 1.0$

$$a_w = \left[\sum W_{ij}^2 a_{rmsi}^2 \right]^{1/2} \tag{2}$$

where j represents the particular frequency weighting (d, k, c, or j) depending on the location and direction (Table 2), i represents the *ith* frequency component, and a_{rmsi} is the measured one-third octave acceleration level at center frequency i. While the ISO 2631-1 does not use the back weighted interface accelerations for assessing comfort, it was done for this study for comparison to the weighted pelvis accelerations. In addition, the ISO 2631-1 only recommends the weighting of the vertical head acceleration using W_j and does not provide specific guidance on comfort based on the head weighted acceleration. In this study, the horizontal head accelerations were also weighted using W_d. For assessing comfort reaction, the point vibration total value (*pVTV*) was calculated as the vector sum of the weighted X, Y, and Z accelerations, after applying the appropriate multiplying factors, at the pelvis interface, back interface (same as pelvis) and head for the litter patient:

$$pVTV = \left[k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2 \right]^{1/2} \tag{3}$$

The *pVTVs* were compared to the weighted accelerations associated with the comfort reactions given in ISO 2631-1: 1997, Annex C. The comfort reactions include “Not Uncomfortable”, “A Little Uncomfortable”, “Fairly Uncomfortable”, “Uncomfortable”, “Very Uncomfortable”, and “Extremely Uncomfortable”.

4.0 RESULTS

All figures and tables referred to in this section are located in the Appendix.

4.1 Characteristics of the AMBUS Acceleration Spectra

Figures A-1 and A-2 illustrate examples of the spectra occurring at the patient/litter interfaces, and at the chest and head for one of the subjects (Subject 2). The data depicted in Figure A-1 was collected at the left mid section of the bus (no bracing). The data depicted in Figure A-2 was collected at the left aft section of the bus (no bracing). For the majority of collected data records, the highest acceleration peaks occurred in the vertical (X) direction between 3 and 4 Hz, primarily at 3 and 3.5 Hz, with smaller peaks observed in the lateral (Y) and longitudinal (Z) directions. A comparison of the figures strongly suggests that higher vertical accelerations occurred in the aft section of the bus as compare to the mid section. This observation is discussed in more detail for the overall unweighted and weighted accelerations. In addition, for Subjects 1 and 2, who were tested at both the left mid and left aft bus sections, several of the data records showed additional peaks in the lateral (Y) direction between 10 and 20 Hz. Both subjects showed that these peaks were higher at the mid section of the bus (note in Figures A-1 and A-2). A few records even showed that the lateral peak between 10 and 20 Hz was higher than the low frequency vertical peak occurring between 3 and 4 Hz. Subject 2 also showed the lateral peaks at the mid section on the right side. As shown in Figure A-1 and suggested in Figure A-2, the peaks between 10 and 20 Hz were most prominent at the pelvis and back interfaces, and were damped at the chest and head. It is not clear what specifically caused the lateral peak at the mid section of the bus. The mid section litter was in close proximity to the wheel well. The lateral peaks occurring between 10 and 20 Hz and their characteristics will be further addressed in the **DISCUSSION**.

4.2 Effects of Bus Section, Bus Side, and Litter Tier

The overall unweighted accelerations calculated between 1 and 80 Hz in accordance with Equation 1 were used to evaluate the effects of mid and aft bus sections (Subjects 1, 2), the left vs right side of the bus (Subjects 1, 2, 3), and the middle tier 2 and highest tier 3 (Subject 3). The paired t-test was applied to the overall unweighted accelerations associated with the targeted test course locations to evaluate the effects. Table A-2 lists the statistical findings. Those results showing significant effects are highlighted in yellow in Table A-2 and marked with a red asterisk in Figures A-3, A-4, and A-5. Figure A-3 depicts the mean overall unweighted acceleration ± one standard deviation at the mid bus and aft bus sections for Subjects 1 and 2 at all five measurement sites. (The vertical (X) leg data collected for Subject 2 at mid bus was corrupt and not included in the analysis.) The most consistent finding was the significantly higher overall vertical (X) accelerations occurring at the aft bus section as compared to the mid bus section for all measurement sites ($P<0.5$). Subject 1 showed statistically higher horizontal (Y, Z) accelerations at the aft bus section for the chest, head, and leg, but this was not necessarily the case for Subject 2. Interestingly, both subjects showed significantly higher overall lateral (Y) back acceleration levels at the mid bus section as compared to the aft bus section ($P<0.05$). This result was most likely contributed to by the higher lateral peaks observed between 10 and 20 Hz

(Figures A-1, A-2). All other overall horizontal accelerations showed variable differences that were relatively small.

Figure A-4 depicts the mean overall unweighted acceleration ± one standard deviation at the left and right side of the bus for all three subjects. The paired t-test indicated that the majority of measurement sites and directions for Subjects 1 and 2 did not show statistically significant differences in the overall acceleration levels between the two sides (Table A-2). Subject 3 showed that about half of the measurement sites and directions showed overall accelerations that were not significantly different, while the other half showed that the overall accelerations were statistically higher at the right side vs left side of the bus. The differences for those measurement sites and directions that showed statistical significance were relatively small, as illustrated in Figure A-4.

Figure A-5 depicts the mean overall unweighted accelerations ± one standard deviation at tier 2 and tier 3 for Subject 3. The paired t-test indicated that about half of the measurement sites and directions showed overall accelerations that were not significantly different, while the other half showed that the overall accelerations were statistically higher at tier 3 vs tier 2, except for the pelvis vertical (X) motion (Table A-2). As with the left and right sides, the differences were relatively small (Figure A-5).

4.3 Effect of Bracing Litters

The effect of bracing the litter by trained AE personnel was evaluated for Subjects 1 and 2 for the litters located on the left side at tier 2, at both the mid and aft sections of the bus. Figures A-6 and A-7 illustrate the overall unweighted back and head accelerations, respectively, at the mid and aft bus sections, in each of the three directions, at each test course location for Subject 1. Figures A-8 and A-9 illustrate the overall unweighted back and head accelerations at each test course location for Subject 2. The paired t-test was applied to the overall unweighted accelerations at all measurement sites and directions associated with the targeted test course locations to evaluate the effects of bracing. Table A-3 lists the statistical findings. The results that showed significant differences between unbraced and braced are highlighted in yellow ($P<0.5$). Significantly higher overall accelerations were observed for the majority of measurement sites with the unbraced litter as compare to the braced litter at the mid bus section for Subject 1 and at the aft bus section for Subject 2. These data were collected during the same course runs (Table 1, Runs 1 and 2). In contrast, the majority of measurement sites showed no significant differences between the unbraced and braced litter at the aft bus section for Subject 1 and at the mid bus section for Subject 2. Likewise, these data were collected during the same course runs (Table 1, Runs 3 and 4).

Regardless of these findings, Figures A-6 through A-9 show that the differences between the unbraced and braced overall accelerations were relatively small and variable throughout the test course, with a few notable exceptions. For example, at the mid bus section, both subjects showed significantly higher overall accelerations at the back interface in the lateral (Y) direction for the braced litter as compared to the unbraced litter (Table A-3, Figures A-6 and A-8). Specifically, the greatest differences tended to occurred where the lateral back accelerations were the highest (note data at test course locations 10 - 12 in Figures 6 and 8). However, at the head, chest, and leg, the overall accelerations were either higher with the unbraced litter or no different from the braced litter (Table A-3). As mentioned previous, the higher frequency lateral accelerations will be further addressed in the **DISCUSSION**.

4.4 Weighted Accelerations and Vibration Total Values (*VTV*s) for Comfort Assessment

It is noted that the ISO 2631-1 only provides guidance for comfort and perception for the supine posture using the measurement at the pelvis interface with the supporting surface. For this study, the overall weighted back accelerations were also calculated using the same frequency weightings and multiplying factors applied to the pelvis interface data. In addition, the weighted vertical (X) accelerations at the head were calculated using frequency weighting W_j, while the weighted horizontal (Y and Z) accelerations at the head were calculated using frequency weighting W_d. As stated previously, the ISO 2631-1 does not provide guidance on comfort based on the head measurements.

Figures A-10 and A-11 illustrate the overall weighted accelerations and *pVTV*s at the pelvis and back interfaces, and the head for Subjects 1 and 2, respectively, at the mid and aft bus sections. The figures include the mean overall weighted accelerations ±one standard deviation. Also included are the comfort reaction categories defined in ISO 2631-1. As suggested by the unweighted data depicted in Figure A-3, the overall weighted pelvis and back accelerations tended to be the highest in the vertical (X) direction. The paired t-test was applied to the mid and aft bus data; significant differences annotated with a yellow asterisk in the figures. As with the overall unweighted accelerations shown in Figure A-3, the paired t-test indicated that the overall weighted pelvis, back, and head accelerations tended to be higher at the aft bus section as compared to the mid bus section.

This is not easily seen for Subject 2 at the pelvis and back. In addition, the longitudinal (Z) pelvis and longitudinal (Z) back data for Subject 2 showed that the mid section data was significantly greater than the aft section data, although the differences were small. While statistical significance was shown for the unweighted head accelerations in all three directions for Subject 1 ($P<0.5$), statistical significance was not observed for the unweighted horizontal head acceleration for Subject 2 ($P\geq0.5$) in contrast to the overall weighted head accelerations (Table A-2). Both subjects showed significantly higher pelvis, back, and head *pVTV*s at the aft bus section as compared to the mid bus section.

With respect to the ISO 2631-1 Comfort Reactions, both subjects showed that the mid bus and aft bus sections generated vertical (X) pelvis and back interface accelerations ranging from "fairly uncomfortable" to "very uncomfortable". Figure A-10 does show that Subject 1 did experience vibration at one test course location associated with being "extremely uncomfortable". The pelvis and back interface *pVTV*s showed results that were similar to the vertical (X) pelvis and back accelerations, indicating very little contribution from the horizontal (Y, Z) motions to comfort as defined in ISO 2631-1; both subjects showing comfort reactions for the horizontal (Y, Z) motions primarily ranging between being "not uncomfortable" to "fairly uncomfortable". Both subjects showed weighted overall head accelerations associated with being considered "a little uncomfortable" to being "uncomfortable", with a few data records associated with being "very uncomfortable". Interestingly, the head *pVTV*s at both bus sections appeared notably higher as compared to the directional data, with some records being considered "extremely uncomfortable" for Subject 2, particularly at the aft bus section (Figure A-11). This indicated that the horizontal (Y, Z) head motions did contribute to the comfort, in contrast to the observations at the litter/occupant pelvis and back interfaces. In addition, and particularly notable for Subject 2, the contribution of the lateral (Y) back interface data between 10 and 20 Hz to the overall unweighted data at the mid cabin section was not observed in the weighted data, most likely due to the frequency weightings (Table 2) that reduced the contribution of the motions in this frequency range.

5.0 DISCUSSION AND CONCLUSIONS

This study sought to collect and characterize vibration transmitted to litter patients during ground transport aboard the AMBUS, located in Area B, WPAFB, OH. Triaxial accelerations were collected at the pelvis and back interfaces where the three subject patients made contact with the litter, and at selected anatomical sites, including the head. The test course was a modification of that used to train the ETTs. Data were collected at 25 targeted locations along the test course. Each test run lasted approximately 20 minutes. A total of six test runs were completed; three without bracing, and three with bracing by trained AE personnel. Each of the three subject patients occupied three different litter locations for comparison.

There were several consistent vibration characteristics and trends revealed from the AMBUS ground tests. All measurement sites showed distinct and prominent acceleration peaks below 5 Hz, with vertical (X) vibration being notably the highest and occurring at 3 or 3.5 Hz. This low frequency vibration is expected during operation of large transport vehicles, such as the AMBUS, and can produce relatively large body displacements. The vertical (X) vibration tended to be higher for the occupants located in the aft section of the bus. The minimal vertical vibration produced at higher frequencies suggested that the low frequency component was the primary contributor to the characteristics of the unweighted overall vertical (X) accelerations. This was not necessarily the case for the horizontal directions, particularly at the mid bus section and particularly in the lateral (Y) direction at the pelvis and back interfaces. At these sites, substantial vibration was observed between 10 and 20 Hz as shown in Figure A-1. It is expected that these higher frequency peaks did influence the calculation of the overall unweighted accelerations used in the data analysis, producing significantly higher overall unweighted lateral (Y) back accelerations at the mid as compared to the aft bus sections (Table A-1).

The higher lateral (Y) peaks observed between 10 and 20 Hz at the mid bus section do warrant further discussion. With reference to Figures A-6 and A-8, the highest overall lateral (Y) back accelerations occurred at test course locations 10 - 12. Review of the spectra data did show that these locations were associated with the highest lateral (Y) peak accelerations at the interfaces. Figure 7 illustrates the back and head spectra at the mid bus section without bracing and with bracing at test location 10 for Subject 2. The magnitudes of the vertical (X) peaks and lateral (Y) peaks (back only) are annotated. The lateral peaks occurred at 12.5 Hz. The figure shows that, with bracing, the lateral (Y) back peak was increased. In contrast, with bracing, a small reduction was observed at the low frequency vertical (X) back peak. Likewise, with bracing, there was a small reduction in the vertical (X) head low frequency peak. Figure 7 also shows lower multi-axis peaks occurring at the head between 10 and 20 Hz, although there appears to be little difference between no bracing and bracing. The relatively high lateral (Y) interface

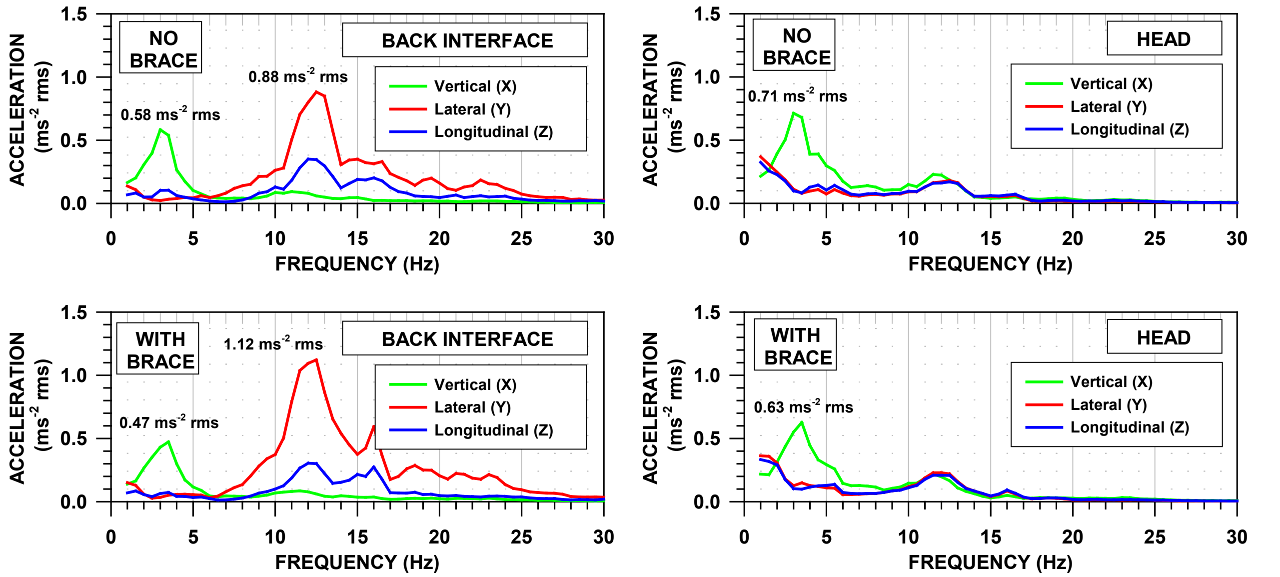

Figure 7. Litter Patient Acceleration Spectra Bracing Effects at Test Location 10.

accelerations were also observed at the mid bus section on the right side for Subject 2. Analysis of the right side lateral (Y) back peaks has not been done at this time. For Subject 1, the overall lateral (Y) back interface peaks between 10 and 20 Hz were also observed to be highest at test course locations 10 – 12 and with the braced litter (Figure A-8). As with Subject 2, the spectra data showed that both the back and head vertical (X) peaks were reduced with the braced condition. Further detailed analysis of the magnitude trends in the low frequency peaks, particularly in the vertical (X) direction, may provide more insight regarding into the effects of litter location and bracing.

In this study, the assumption was made that, in general, the vibration transmitted to the litters would be similar at the same course locations for all runs. While the driver made all attempts at consistency between runs, this may not have been easily accomplished, particularly with regard to the bus speed. Likewise, the bracing behavior can be expected to varying throughout the test course and between runs, depending heavily on how quickly higher loads were perceived and action taken by the AE personnel. Effective bracing would also depend on the ability of the AE personnel to stabilize their own motions when traveling over rough terrain. Regardless of these variabilities, and how they may have affected the vibration characteristics, the results of this study emphasizes the complexity of the multi-axis vibration generated during AMBUS transport.

While the results of this study, and the complexity of the vibration noted above, render the effects of bracing inconclusive, it certainly does not mean that this type of activity should not be attempted by AE personnel during ground transport over rough terrain. Especially if alternative methods are not available. The goal is to reduce the low frequency vibration shown to be prevalent during AMBUS transport since the larger motions could certainly compromise the condition of those patients with head or spinal injury. This calls for the development of head and spine immobilization techniques that do not rely on the AE personnel actively attempting to brace the litter and perhaps jeopardizing their ability to administer medical treatment.

The overall weighted accelerations and *pVTV*s depicted in Figures A-10 through A-12 indicated that the vibration exposure during AMBUS transport would range between being considered “fairly uncomfortable’ to “very uncomfortable” for healthy individuals. However, as mentioned previously, the ISO 2631-1 comfort reactions were approximated based on passenger expectations during public transport. The comfort reaction thresholds are expected to be lower for the injured patient during emergency evacuation and transport, and could vary dramatically depending on the type of injury, treatment regime, type of transport, and transport duration. In addition, and of high importance, is that the lower frequency vibration associated with ground transport aboard the AMBUS could exacerbate injury, particularly to the spine and head.

6.0 RECOMMENDATIONS

1. It is recommended that the most critically injured patients be located in the mid section of the AMBUS where the lower frequency vibration and associated motion may be reduced.
2. Develop patient body motion mitigation concepts for minimizing adverse health outcomes, particularly at lower frequencies below 10 Hz, alleviating the AE personnel from active attempts to use their own bodies to reduce the vibration. These concepts should target litter mounting and support techniques, as well as patient restraint systems.
3. Existing vibration exposure guidelines apply to healthy persons and should be cautiously applied to the injured patient. It is expected that the injured patient comfort thresholds could be dramatically lower depending on the injury, treatment regime, flight conditions and flight duration. Further research is required to develop guidelines for the injured patient.

7.0 REFERENCES

Couvreur, C., *FILTBANK - One-Third-Octave Band Frequency Analyzer* [computer program, MATLAB®], Faculte Polytechnique de Mons, Belgium, 1997.

Department of Defense, *Department of Defense Design Criteria Standard, Human Engineering*, MIL-STD-1472G, 11 Jan 2012.

International Organization for Standardization, *Mechanical vibration and shock-Evaluation of human exposure to whole-body vibration-Part 1: General requirements*, ISO 2631-1: 1997. Geneva, Switzerland.

International Organization for Standardization, *Mechanical vibration and shock-Evaluation of human exposure to whole-body vibration-Part 1: General requirements-Amendment 1*, ISO 2631-1/Amd1:2010. Geneva, Switzerland.

Smith, S. D., Burch, D. S., Fouts, B. L., *Quantifying Patient Vibration Patterns During Aeromedical Evacuation Aboard the C-130H,* AFRL-RH-WP-TR-2019-0086, Air Force Research Laboratory, Human Effectiveness Directorate, Wright-Patterson AFB OH, 2019.

Welch, P. D., "The Use of Fast Fourier Transform for the Estimation of Power spectra: A method Based on Time Averaging Over Short, Modified Periodograms," *IEEE Trans. Audio Electroacoust.*, **AU-15**, Jun 1967, pp. 70-73.

APPENDIX: RESULTS - FIGURES AND TABLES

LIST OF FIGURES

LIST OF TABLES

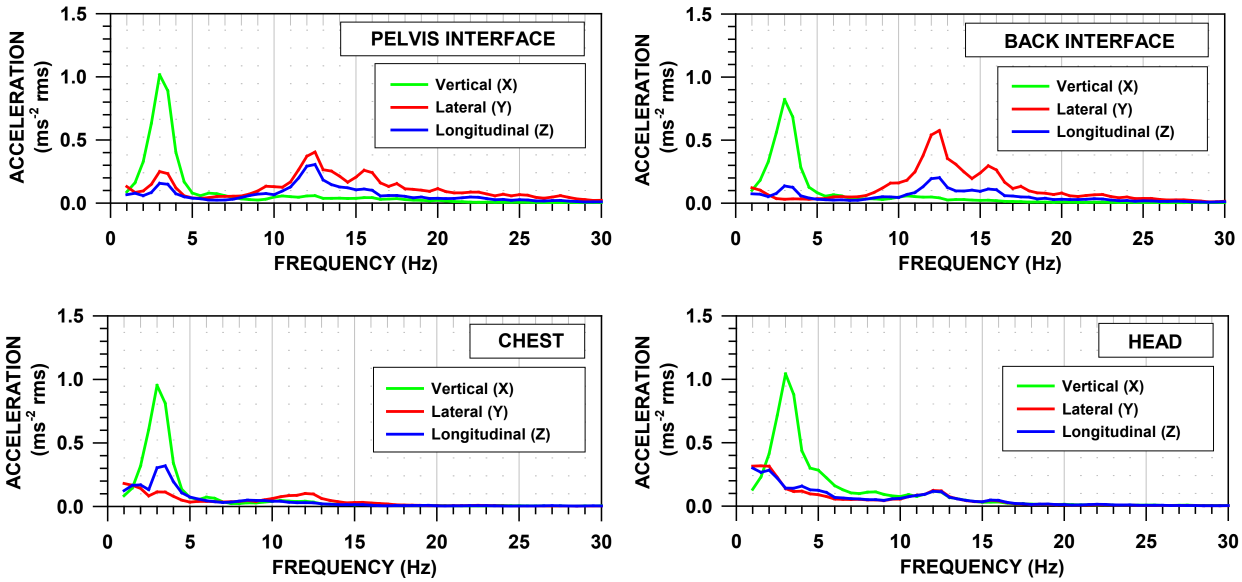

Figure A-1. Examples of Litter Patient Acceleration Spectra (Subject 2, Left Side, Mid Bus, Tier 2)

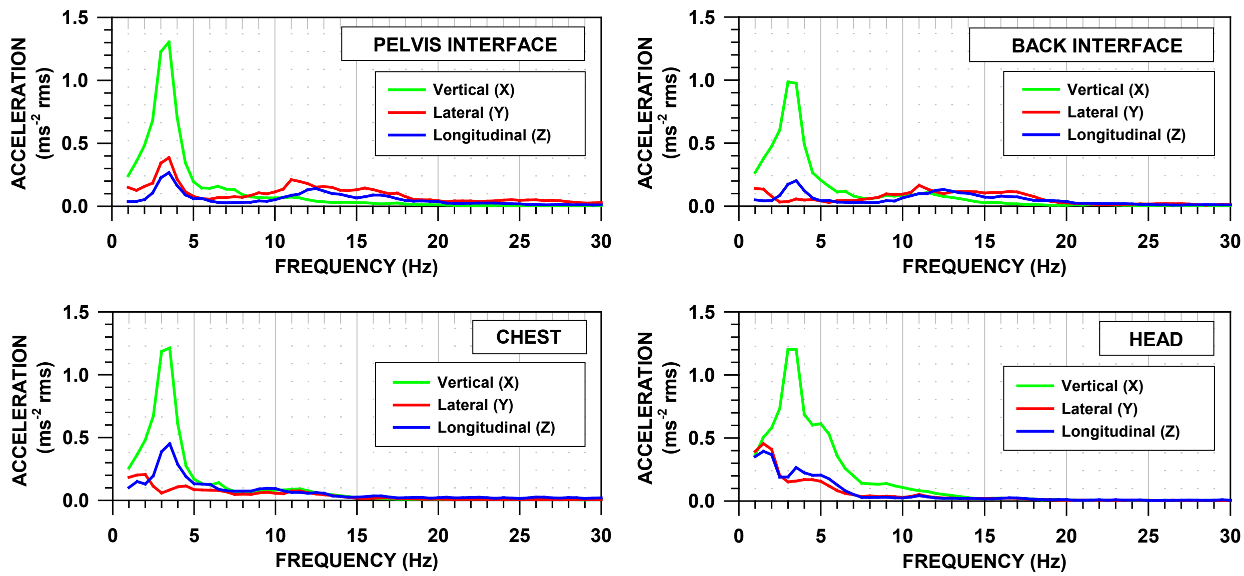

Figure A-2. Examples of Litter Patient Acceleration Spectra (Subject 2, Left Side, Aft Bus, Tier 2)

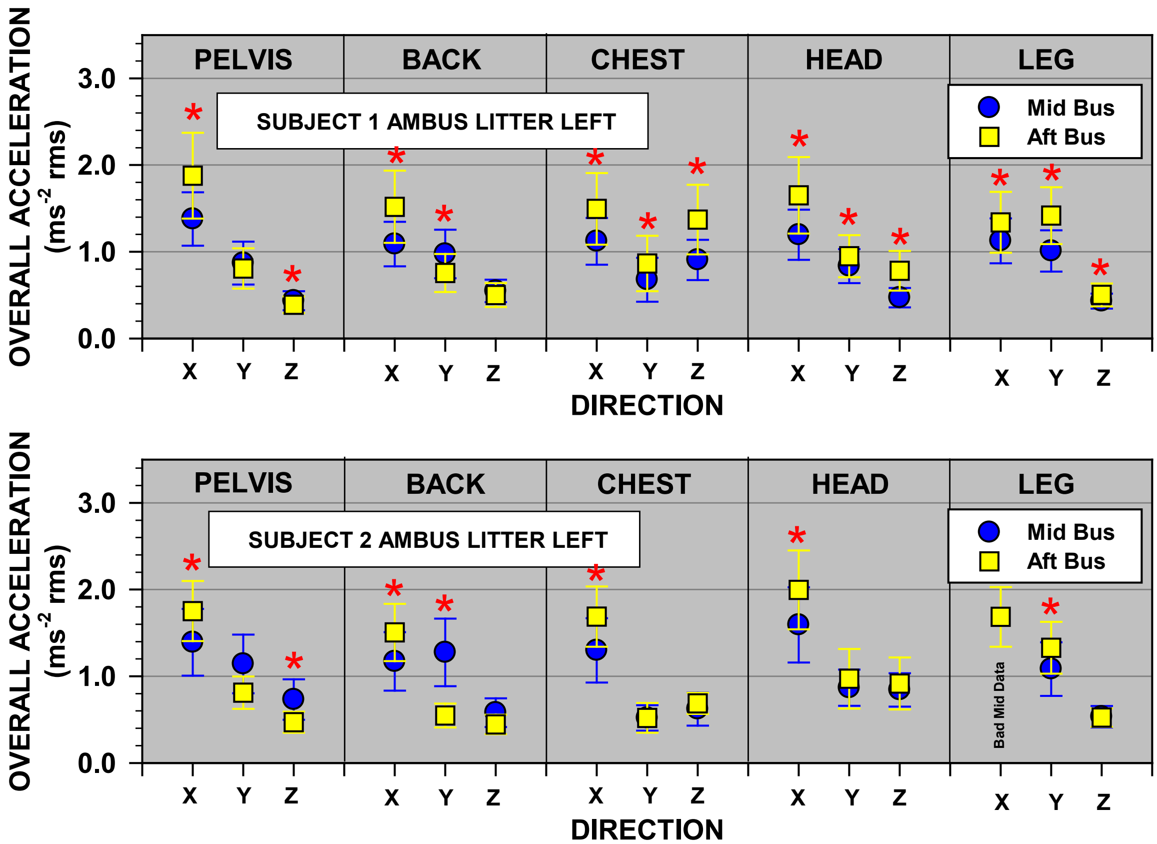

Figure A-3. Mean Overall Unweighted Accelerations ± One Standard Deviation: Mid vs Aft Litter Location (Note: X (Vertical), Y (Lateral), Z (Longitudinal))

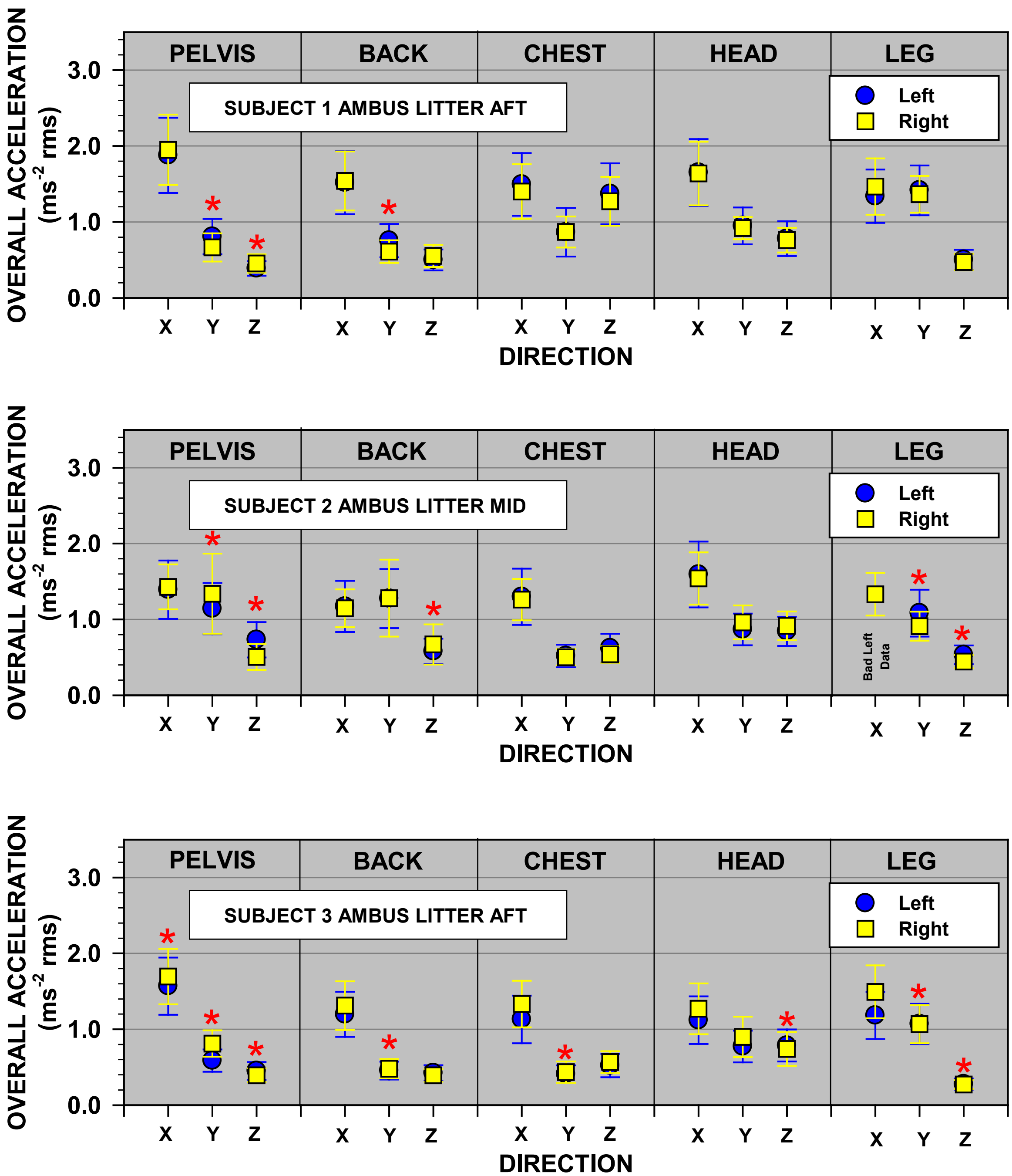

Figure A-4. Mean Overall Unweighted Accelerations ± One Standard Deviation: Left vs Right Litter Location (Note: X (Vertical), Y (Lateral), Z (Longitudinal))

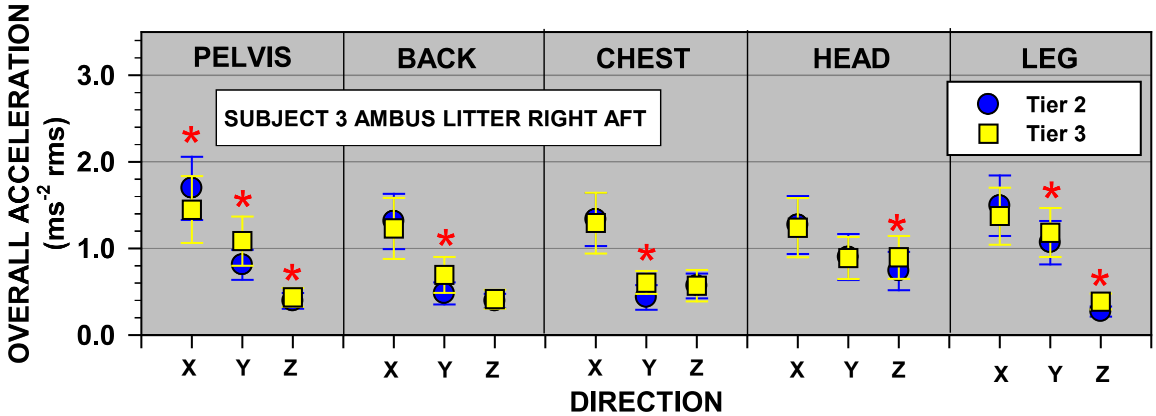

Figure A- 5. Mean Overall Unweighted Accelerations ± One Standard Deviation: Tier 2 vs Tier 3

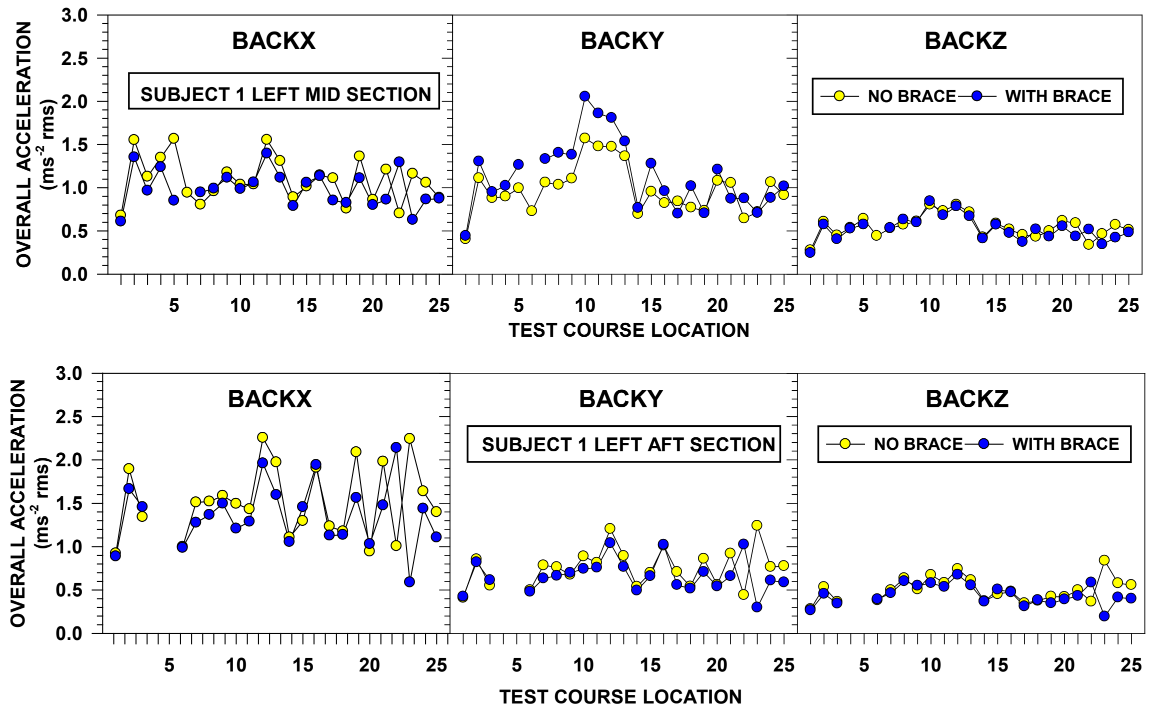

Figure A- 6. Subject 1 Overall Unweighted Back Accelerations at Mid and Aft Bus Sections: Effect of Bracing (Note: X (Vertical), Y (Lateral), Z (Longitudinal))

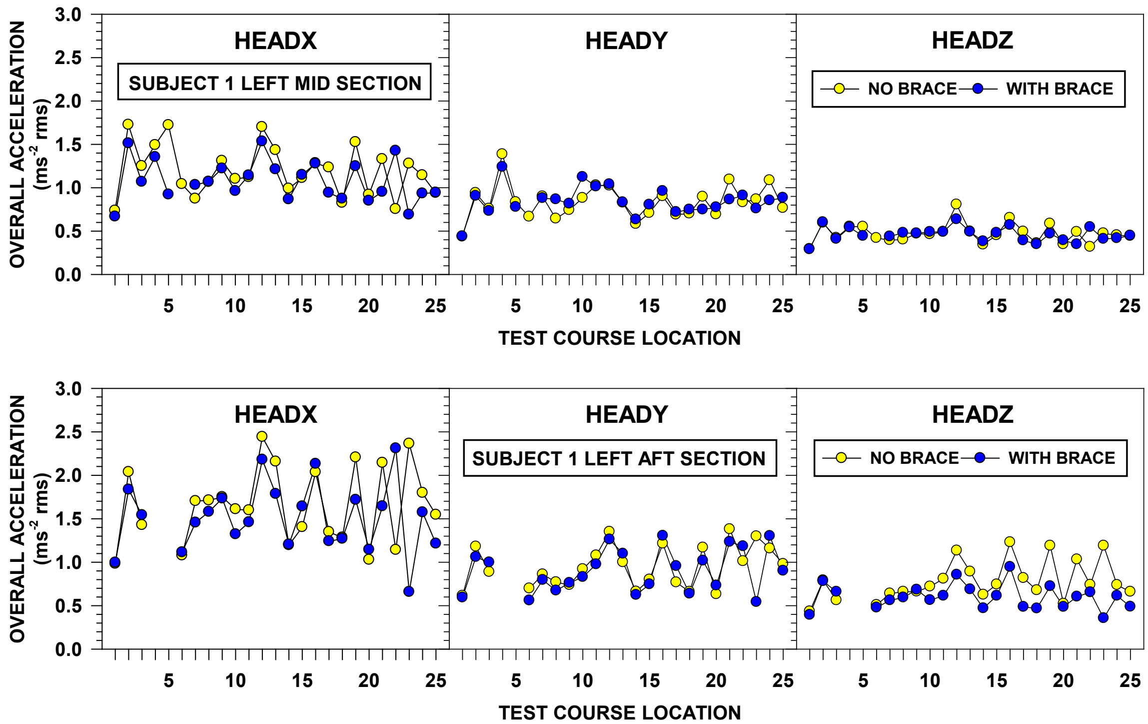

Figure A- 7. Subject 1 Overall Unweighted Head Accelerations at Mid and Aft Bus Sections: Effect of Bracing (Note: X (Vertical), Y (Lateral), Z (Longitudinal))

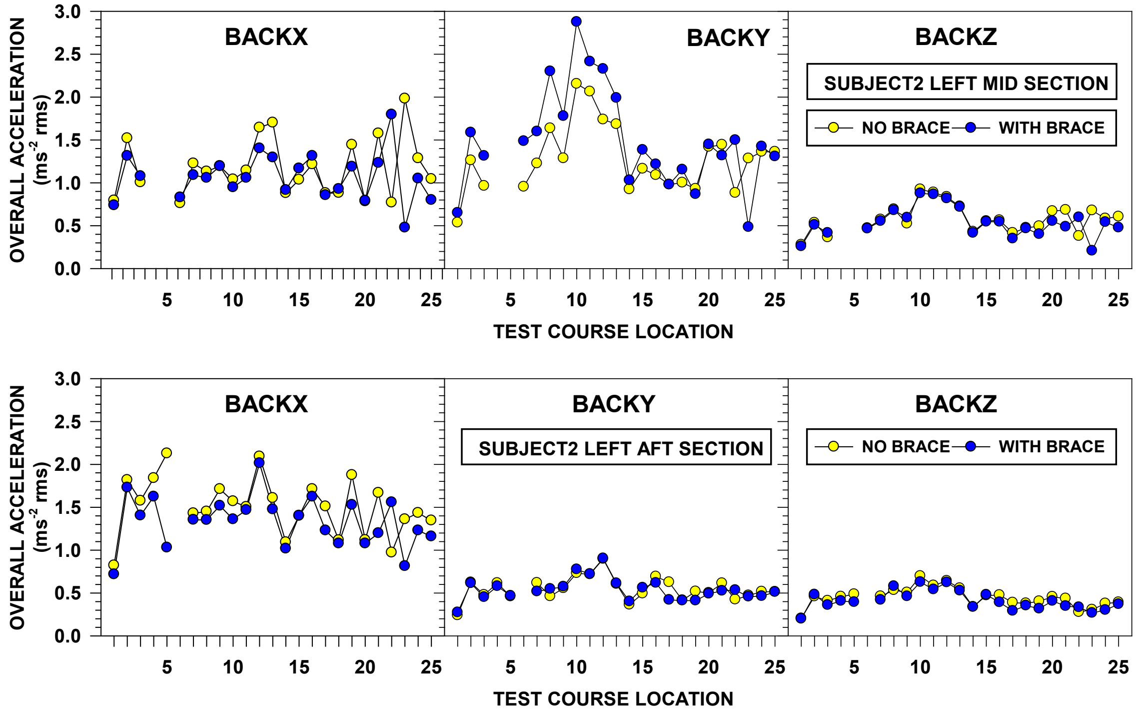

Figure A- 8. Subject 2 Overall Unweighted Back Accelerations at Mid and Aft Bus Sections: Effect of Bracing (Note: X (Vertical), Y (Lateral), Z (Longitudinal))

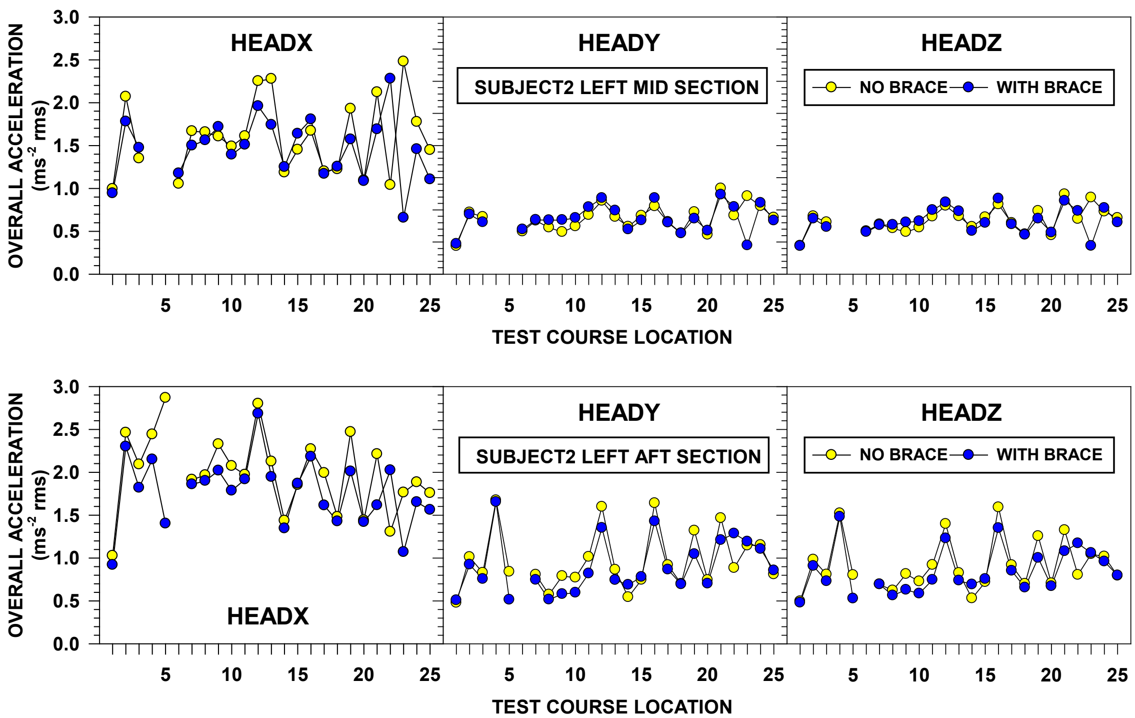

Figure A- 9. Subject 2 Overall Unweighted Head Accelerations at Mid and Aft Bus Sections: Effect of Bracing (Note: X (Vertical), Y (Lateral), Z (Longitudinal))

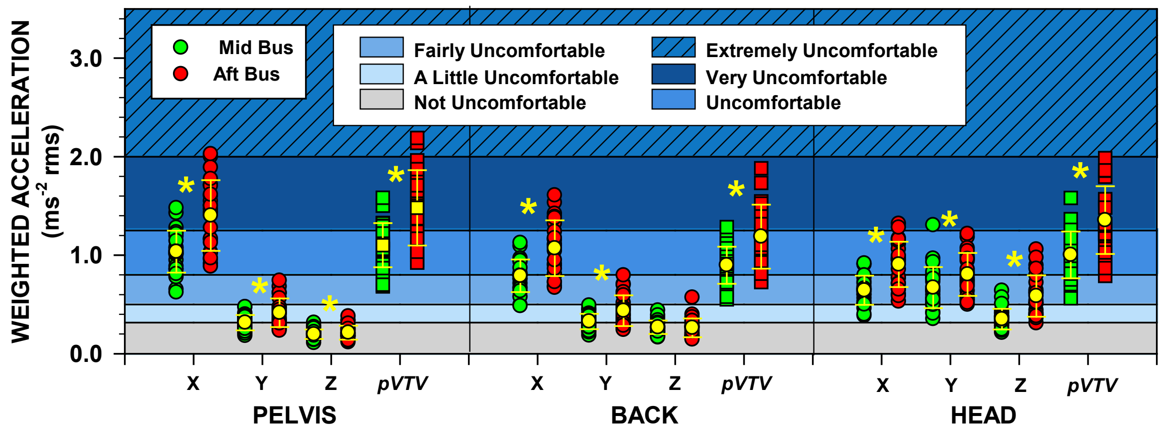

Figure A- 10. Subject 1 Overall Weighted Accelerations and *pVTV*s at the Mid and Aft Bus Sections (Note: X (Vertical), Y (Lateral), Z (Longitudinal))

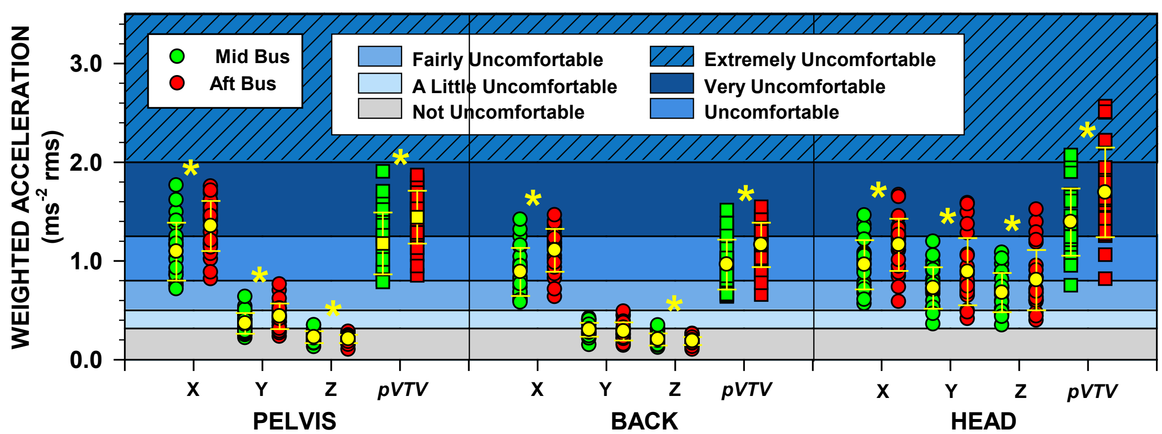

Figure A- 11. Subject 2 Overall Weighted Accelerations and *pVTV*s at the Mid and Aft Bus Sections (Note: X (Vertical), Y (Lateral), Z (Longitudinal))

Table A-1. REVER Component Details

Component	Dimensions (L/W/H cm)	Weight (Kg)	Item Identification or Number
DAU (PicoDas)	9.5/6.0/2.9	0.370 w/cables	EME S/N 04-22
			EME S/N 10-31
			EME S/N 10-41
Large Batteries	10.0/7.0/3.5	0.645	TOTAL: 3
Small Batteries	9.0/5.0/3.5	0.395	TOTAL: 3
Accelerometer Packs	1.9 (diameter) 0.86 (thickness)	0.005 (0.060 w/ cable)	TOTAL: 9 (3 accelerometers each)
Acceleration Pads	20.0 (diameter)	0.340 w/ cables	TOTAL: 6 (1 accelerometer pack each)
Triggers	7.6 (length) 2.2 (diameter)	0.030 w/cable	TOTAL: 3
Extension Cables	Various lengths	-	

Table A-2. Paired t-Test Statistics Results (Significance at P<0.5)

		MID VS AFT		LEFT VS RIGHT			TIER 2 VS TIER 3
	Direction	Subject 1	Subject 2	Subject 1	Subject 2	Subject 3	Subject 3
PELVIS	X	A>M	A>M	R=L	R=L	R>L	T2>T3
	Y	A=M	A=M	L>R	R>L	R>L	T3>T2
	Z	M>A	M>A	R>L	L>R	R>L	T3>T2
BACK	X	A>M	A>M	R=L	R=L	R=L	T2=T3
	Y	M>A	M>A	L>R	R=L	R>L	T3>T2
	Z	A=M	A=M	R=L	R>L	R=L	T2=T3
CHEST	X	A>M	A>M	R=L	R=L	R=L	T2=T3
	Y	A>M	A=M	R=L	R=L	R>L	T3>T2
	Z	A>M	A=M	R=L	R=L	R=L	T2=T3
HEAD	X	A>M	A>M	R=L	R=L	R=L	T2=T3
	Y	A>M	A=M	R=L	R=L	R=L	T2=T3
	Z	A>M	A=M	R=L	R=L	R>L	T3>T2
LEG	X	A>M	A>M	R=L	R>L	R=L	T2=T3
	Y	A>M	A>M	R=L	L>R	R>L	T3>T2
	Z	A>M	A=M	R=L	L>R	R>L	T3>T2

A=Aft L=Left M=Mid R=Right T2=Tier 2 T3=Tier 3
Note: X (Vertical), Y (Lateral), Z (Longitudinal)

Table A-3. Paired t-Test Statistics Results, Braced vs Unbraced Litters (Significance at P<0.5)

		SUBJECT 1		SUBJECT 2	
	Direction	Mid Bus Section	Aft Bus Section	Mid Bus Section	Aft Bus Section
PELVIS	X	U>B	U>B	U=B	U>B
	Y	B>U	B=U	U=B	U>B
	Z	U>B	U>B	U=B	U>B
BACK	X	U>B	U=B	U=B	U>B
	Y	B>U	U=B	B>U	U=B
	Z	U=B	U=B	U=B	U>B
CHEST	X	U>B	U>B	U=B	U>B
	Y	U>B	U=B	U>B	U=B
	Z	U>B	U=B	U>B	U>B
HEAD	X	U>B	U=B	U=B	U>B
	Y	U=B	U=B	U=B	U>B
	Z	U=B	U=B	U=B	U>B
LEG	X	U>B	U=B	U=B	U>B
	Y	U>B	U>B	U=B	U>B
	Z	U>B	U>B	U=B	U>B
U=Unbraced B=Braced	Note: X (Vertical), Y (Lateral), Z (Longitudinal)				

LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

711 HPW	711 Human Performance Wing
AFRL	Air Force Research Laboratory
AMBUS	Ambulance Bus
CBDN	Collaborative Biomechanics Data Network
DAU	Data Acquisition Unit
HGCZs	Health Guidance Caution Zones (ISO 2631-1, Annex B)
Hz	Herz (cycles per second)
ISO	International Organization for Standardization
MIL-STD	Military Standard
REVER	Remote Vibration Environment Recorder
RH	Airman Systems Directorate
RHB	Airman Biosciences Division
RHBF	Biomedical Impact of Flight Branch
rms	Root-Mean-Square
a_{rms}	Root-Mean-Square Acceleration
a_{uw}	Overall Unweighted Acceleration Level
a_w	Overall Weighted Acceleration Level
k	Multiplying Factor (ISO 2631-1)
oVTV	Overall Vibration Total Value
pVTV	Point Vibration Total Value
W	Frequency Weighting (ISO 2631-1)