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QUANTIFYING PATIENT VIBRATION PATTERNS DURING AEROMEDICAL EVACUATION (AE) ABOARD THE UH-60L EQUIPPED WITH THE INTERIM MEDEVAC MISSION SUPPORT SYSTEM (IMMSS)

Suzanne D. Smith PhD
Consultant/Research Engineer, Infoscitex

Steven G. Chervak
Army Public Health Center

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Interim Report

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//signature//
CORY M. WILLIAMS, Capt, USAF
Work Unit Monitor
Biomedical Impact of Flight Branch

//signature//
COREY R. HART, PhD
Core Research Area Lead
Biomedical Impact of Flight Branch
Airman Biosciences Division

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Suzanne D. Smith*
Steven G. Chervak**

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*Consultant, Infoscitex, WPAFB, OH
** Army Public Health Center, Aberdeen Proving Ground, MD

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14. ABSTRACT The purpose of this flight test program was to collect human engineering data on the UH-60L, fitted with the Interim Medevac Mission Support System (IMMSS), to characterize and assess the exposure of patients to vibration during aeromedical evacuation (AE). The aircraft was owned and operated by the Maryland Army National Guard (MD ARNG) located at Aberdeen Proving Ground, MD. The Remote Vibration Environment Recorder (REVER) was used to collect tri-axial acceleration data at the back/pelvis interfaces, chest, head, and support platform of the supine litter patient at two tier levels on the IMMSS, and at the seat pan and seat back interfaces, and seat support bar of a seated patient. Data were collected for multiple flight test conditions aboard the aircraft. All measurement sites showed a major spectral peak in the three directions at approximately 17 – 17.5 Hz; the blade passage frequency of the UH-60. The litter patients showed the highest overall unweighted interface accelerations in the horizontal directions, with higher levels tending to occur at the upper Tier 2. The seated patient showed the highest overall seat pan accelerations in the vertical direction. Litter patients showed damped vibration at the head and chest. The overall weighted accelerations used to assess comfort indicated that the litter patient exposures would primarily be considered "fairly uncomfortable" (ISO 2631-1: 1997), and that the seated patient exposures would be considered "fairly uncomfortable" as well as "uncomfortable", particularly during hover and approaches. It is strongly emphasized that the comfort reactions defined in ISO 2631-1 are based on the reactions expected of relatively healthy seated occupants during public transport, and not traumatically injured patients. While the standard litter used in this project did not include a cushioned mat, it is recommended that this be done during actual medical transport, if not already, for improving the injured patient's comfort. It is expected that, during medical transport, only minimally injured patients would be placed in the seated location. Given the comfort reactions revealed in this project, it is recommended that some type of cushion be placed between the buttocks and seat pan surface to improve seated patient comfort. With respect to the UH-60L equipped with the IMMSS, it is recommended that the most seriously injured patients be located at Tier 1. In addition, for those patients suffering head or spine injury, it is advisable to include additional restraint to restrict upper torso motion.

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1.0 SUMMARY

The overall purpose of this flight test program was 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 are used to conduct a comfort assessment of the exposures in accordance with existing standards. The data are also 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 collecting vibration data for two supine litter patients and one seated patient during aeromedical transport aboard the UH-60L.

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 Air Force Medical Service (AFMS) Strategic Objectives A1, E3, and E6, and will help bridge the gaps identified by the 2014 AFMS Doctrine Change Recommendation (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 Committee 6/Combat Casualty Care 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 UH-60L aircraft was owned and operated by the MD ARNG located at Aberdeen Proving Ground, MD. The Remote Vibration Environment Recorder (REVER) was used to collect tri-axial acceleration data at the back/pelvis interfaces, chest, head, and support platform of the two supine litter patients secured to the Interim Medevac Mission Support System (IMMSS) (Tiers 1 and 2), and at the seat pan/seat back interfaces and seat support bar of the seated patient. Flight conditions included taxi, take off, hover, climb, level flight, turns, approaches, descent, and landing.

All measurement sites showed a major spectral peak in the three directions at approximately 17-17.5 Hertz (cycles per second) (Hz) that was associated with the blade passage frequency of the aircraft. During Flights 1 and 2, the highest overall unweighted vibration at the pelvis and back litter interfaces occurred in the horizontal (Y and LZ) directions at both Tiers 1 and 2. The overall unweighted accelerations indicated that the lowest pelvis and back litter interface vibration tended to occur in the vertical (VX) direction at both tiers. During both flights, the highest overall unweighted vibration at the seat measurement sites tended to occur in the vertical (Z) direction for most flight test conditions.

The overall frequency-weighted accelerations, described as vector sums or Vibration Total Values (*VTV*s), did indicate that, particularly at the litter back interface, and particularly during higher airspeeds, the litter patients were exposed to vibration levels that would be considered "fairly uncomfortable" in accordance with the Organization for Standardization (ISO) 2631-1. Likewise, the seated patient was exposed to vibration levels during higher level flight airspeeds that would be considered "fairly uncomfortable" and "uncomfortable", with high levels of discomfort associated with hover and approaches.

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It is strongly emphasized that the comfort reactions defined in ISO 2631-1 are based on the reactions expected of relatively healthy seated occupants during public transport, and not traumatically injured patients. While the standard litter used in this project did not include a cushioned mat, it is recommended that a cushioned mat be used during actual medical transport, if not already, for improving the injured patient's comfort. It is expected that, during medical transport, only minimally injured patients would be placed in the seated location. Given the comfort reactions revealed in this project, it is recommended that some type of cushion be placed between the buttocks and seat pan surface to improve seated patient comfort. With respect to the UH-60L equipped with the IMMSS, it is recommended that the most seriously injured patients be located at Tier 1. In addition, for those patients suffering head or spine injury, it is advisable to include additional restraint to restrict upper torso motion.

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2.0 INTRODUCTION

As one of the stressors of military flight, vibration can affect occupant physical, physiological, and psychological responses, resulting in increased fatigue, discomfort, and heightened health risks. During AE, patients are exposed to vibration that could not only exacerbate patient medical condition but challenge the ability of medical personnel to monitor patient status and administer medical procedures (Fromm, R. and Duvall, J, 1990). Research on the effects of vibration on patients and litter systems during AE aboard military fixed-wing and rotary-wing aircraft is critically limited.

Four studies have been completed by the Air Force Research Laboratory (AFRL) 711 Human Performance Wing (HPW) onboard military emergency evacuation transport vehicles to characterize and assess patient vibration exposure. The first study targeted the C-130H (Smith S. D. et al. 2019); the second study targeted the C-130J (Smith, S.D. et al. 2021), the third study targeted the Ambulance Bus (AMBUS) ground vehicle (Smith S. D. et al., 2019), and the fourth study targeted the UH-60L Blackhawk. This report documents the patient vibration measured aboard the UH-60L during flight conditions representative of AE.

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 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 and is independent of time. However, guidance on the assessment of health risk is currently limited to the seated posture for daily repeated exposures, and is time dependent, 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 and seated patient vibration exposures during transport aboard the UH-60L configured with the IMMSS.
2. Assess the vibration exposures at the patient/litter and patient/seat 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

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3.0 METHODS AND PROCEDURES

The mention of any non-federal entity and/or its products is for informational purposes only, and not to be construed or interpreted, in any manner, as federal endorsement of that non-federal entity or its products.

3.1 Overview

The AFRL 711 HPW prepared all required documentation including a Flight Test Plan (FTP), and conducted all required review boards including the Technical Review Board (TRB) and Safety Review Board (SRB), in accordance with Air Force Research Laboratory Instruction (AFRLI) 61-103, Scientific Research and Development, AFRL Research Test Management (2015). The study was approved by the AFRL Institutional Review Board (IRB) for human use (FWR-2015-0143-H). The aircraft and aircrew were provided by the MD ARNG located at Aberdeen Proving Ground, MD. This aircraft is similar to the platform that was used to characterize and assess aircrew vibration, which was also supported by the MD ARNG (Smith. S.D. et al., 2019).

REVERs were used to collect the acceleration data at two litter locations and one seat location in the cabin of the aircraft. The installation of the system components onto the litters, seat, and volunteer subject patients was similar to that used in the previous studies. A mockup installation was accomplished to obtain flight clearance approval from the Department of the Army, US Army Research, Development and Engineering Command, Aviation and Missile Research, Development, and Engineering Center, Redstone Arsenal, AL.

Two flights were conducted aboard the UH-60L for collecting patient vibration. Three volunteers acted as patients; two were dedicated as litter patients secured into the IMMSS located on the right side of the cabin, and one was dedicated as the seated patient located in a cloth seat attached to the left sidewall of the cabin.

3.2 Equipment, Instrumentation, and Measurement Sites

Three REVERs, developed by the AFRL Airman Systems Directorate (711 HPW/RH), were used to collect the multi-axis vibration data during the test flights. Each REVER included the following components (Figure 1):

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
6. Connection/extension cables as required

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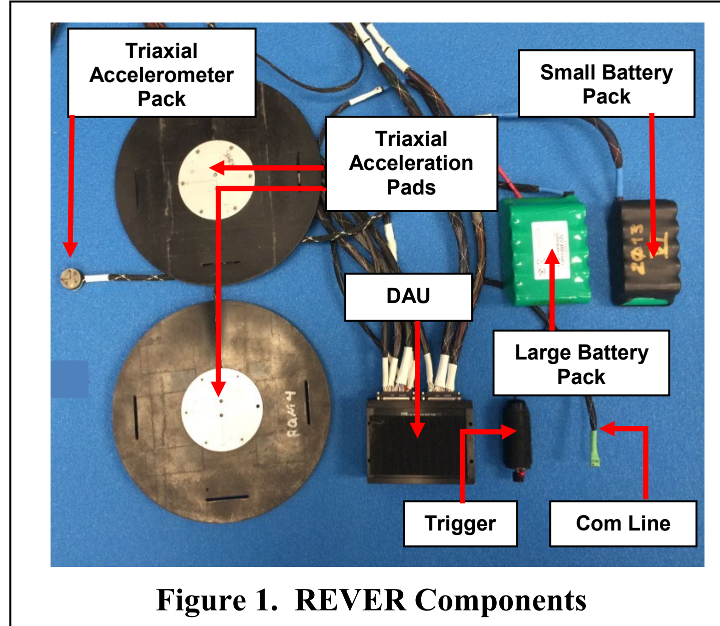

Figure 1. REVER Components

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 ampere (amp)-hours and can operate for approximately 4 hours. Each triaxial accelerometer pack includes three orthogonally-arranged miniature accelerometers (Entran EGAX-25, Entran Devices, Inc., Fairfield, NJ; EGAXT-25, TE Connectivity, Berwyn, PA) embedded in a Delrin® cylinder. Double-sided adhesive tape or mounting tape was used to secure the pack to the appropriate sites. The triaxial acceleration pad is a flat rubber disk that includes an embedded triaxial accelerometer pack. The pads were 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. Details regarding the REVER components are provided in the Appendix, Table A-1.

Figure 2 illustrates the IMMSS where two patient litters were located, as well as the patient seat. It is noted that the Tier 1 litter is attached at the four corners to a support plate mounted onto the floor. At Tier 2, the support plate and litter are cantilevered from the aircraft cabin sidewall (Figure 2). One REVER system was required for measuring the vibration for each supine patient/litter configuration. The DAU and battery packs were attached to the litter between the participant's feet and secured with duct tape (Figure 3, shown for Litter A). 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 directly attached to the participant's chest using double-sided adhesive tape (Figure 4). A triaxial pack was attached to a bite bar (Figure 5) using double-sided adhesive tape for measuring head translation. A triaxial accelerometer pack was also attached to the center of each litter support plate using double-sided

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adhesive tape (Figure 6). Packs attached to the body were further secured with medical tape, as necessary. Cables from the bite bar pack, chest pack, back pad, and pelvis pad were secured to the side of the litter using duct tape. 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 patients were restrained using a chest strap and leg strap. Figure 6 illustrates an instrumented patient configured in Litter A.

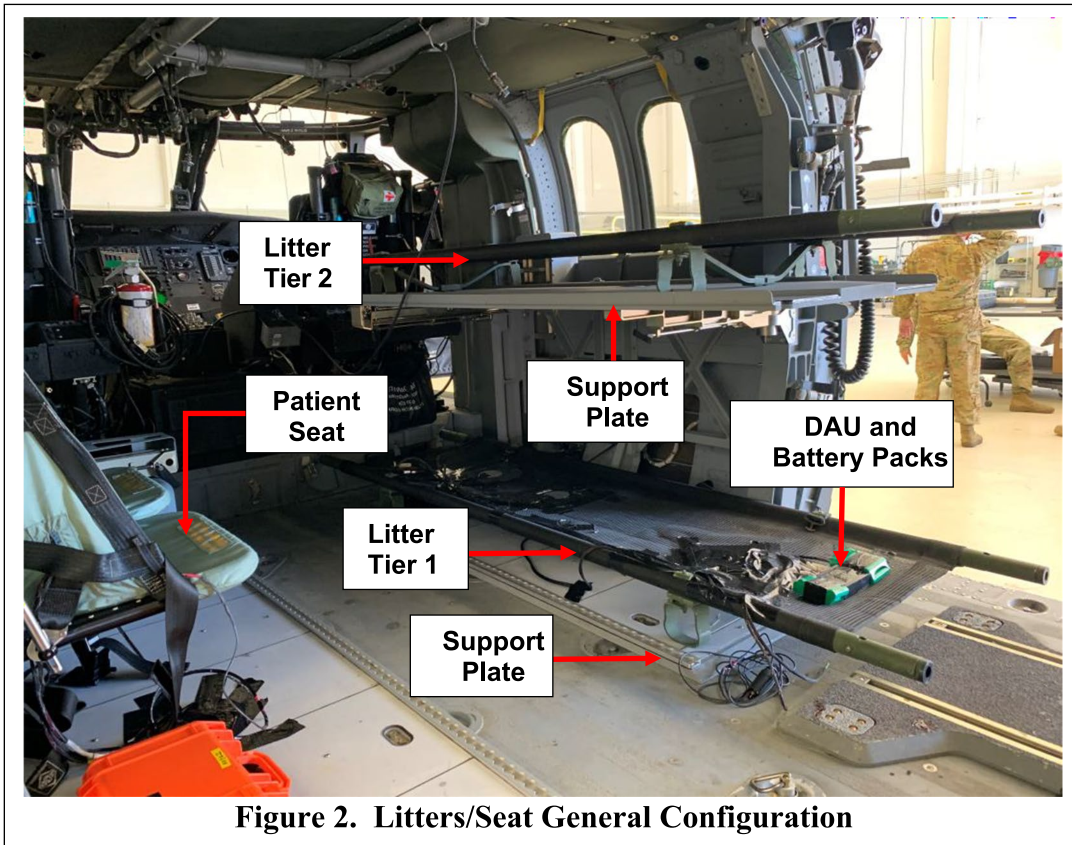

Figure 2. Litters/Seat General Configuration

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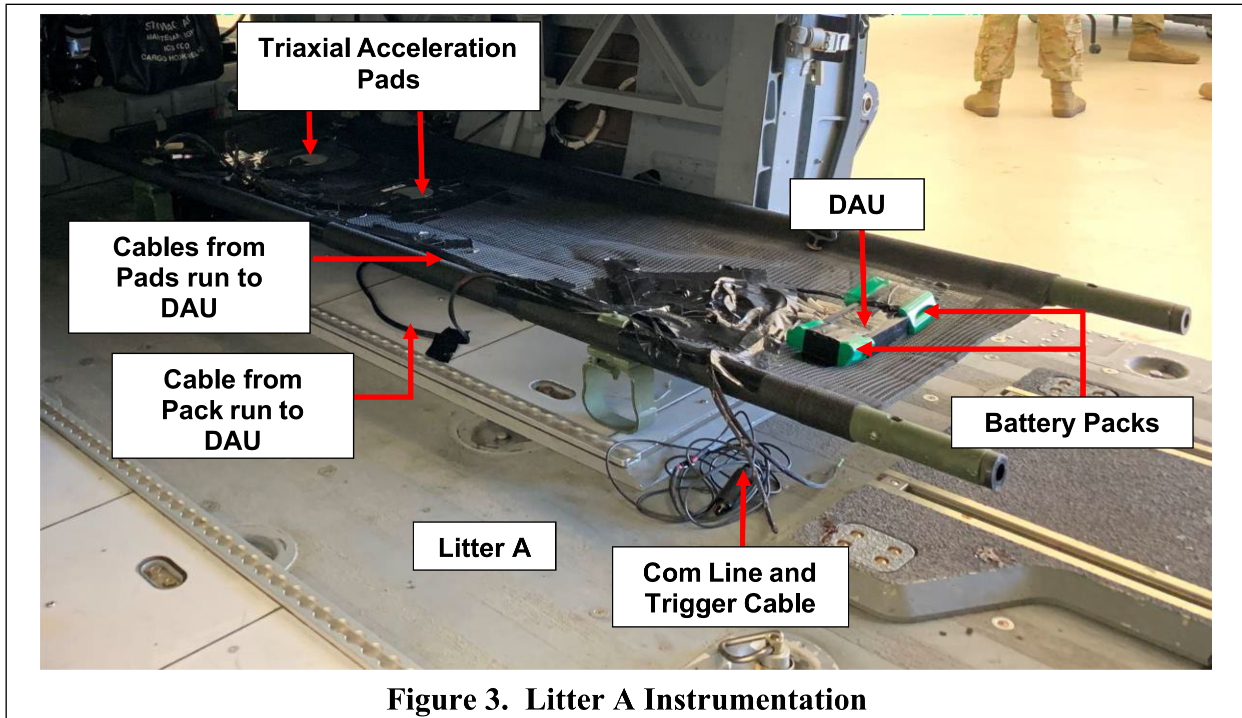

Figure 3. Litter A Instrumentation

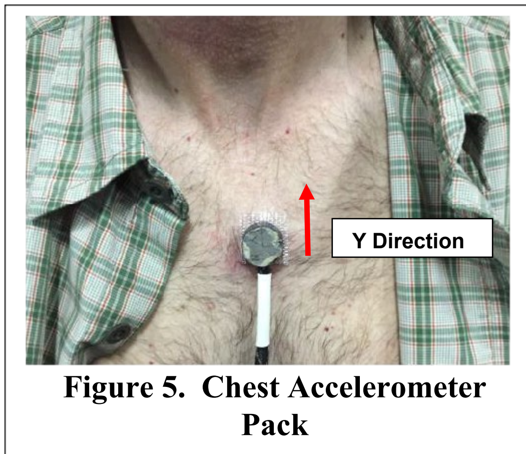

Figure 5. Chest Accelerometer Pack

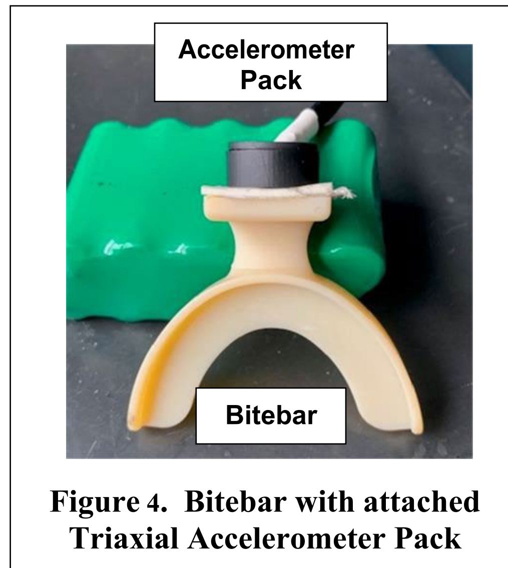

Figure 4. Bitebar with attached Triaxial Accelerometer Pack

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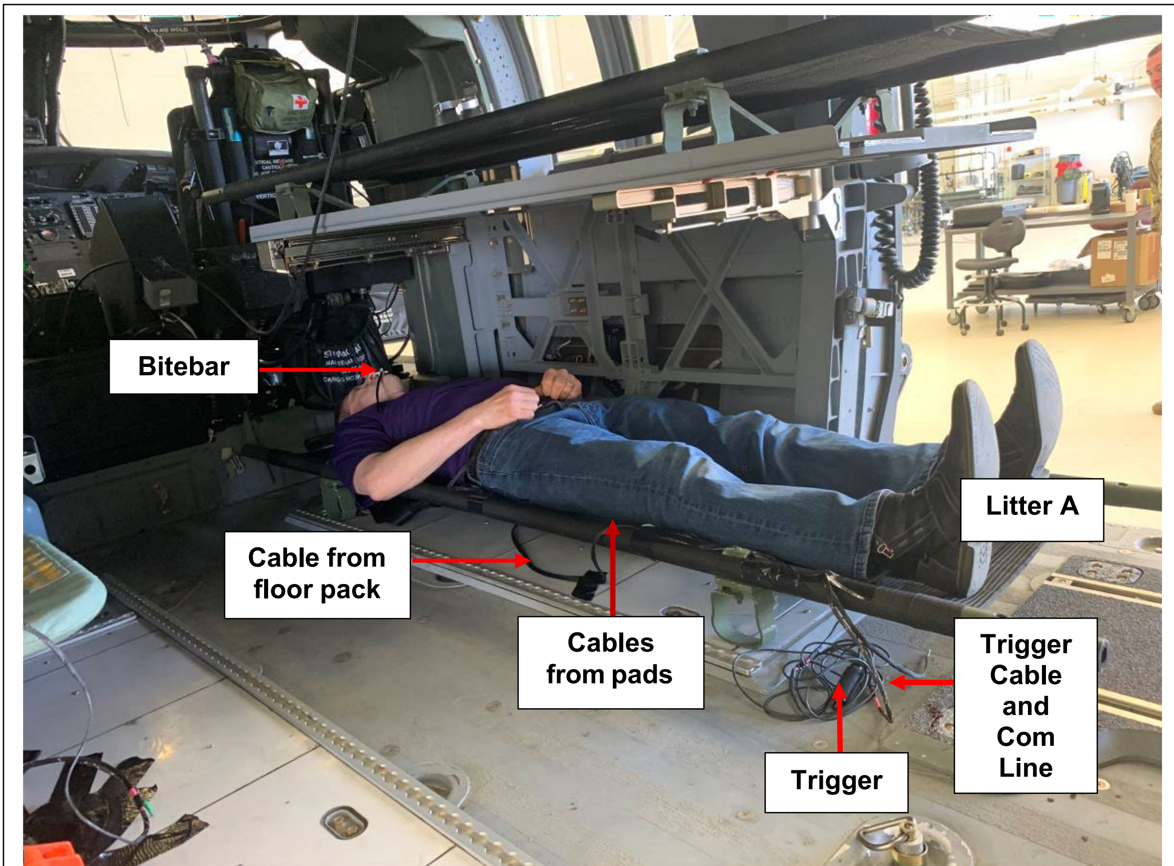

Figure 6. Supine Litter Patient, Litter A

One REVER system was used to measure vibration of the seated patient configuration. The DAU and battery packs were contained in a Pelican case that, in turn, was attached to the floor (Figure 7). Triaxial acceleration pads were placed at the interfaces between the patient's buttocks and seat pan and between the patient's back and seat back (Figure 7). Both were attached with double-sided adhesive tape and secured with duct tape. A triaxial accelerometer pack was attached to the rigid metal seat support bar located behind the seat (not shown). All cables were routed to the Pelican case and secured to avoid any discomfort or hazard to the patient and test support personnel, particularly in the case of an emergency egress. The seated patient was restrained using the available seat restraint system.

A laptop computer system was used for initial calibrations, setup of the instrumentation, and to arm the system prior to the flight test. 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 flight.

A triggering device (Figure 1) was used to initiate data. Once triggered, the DAU would collect data for a pre-specified amount of time. Prior to flight, a laptop computer was used to conduct sensor balance, check sensor calibration, and arm each DAU. The computer was used to assign a specific sensor for each measurement site and direction to a specific channel in the DAU. Once

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armed, the computer was disconnected from the DAU. Upon return of the aircraft, the laptop was reconnected to the DAU and all channels downloaded for subsequent processing.

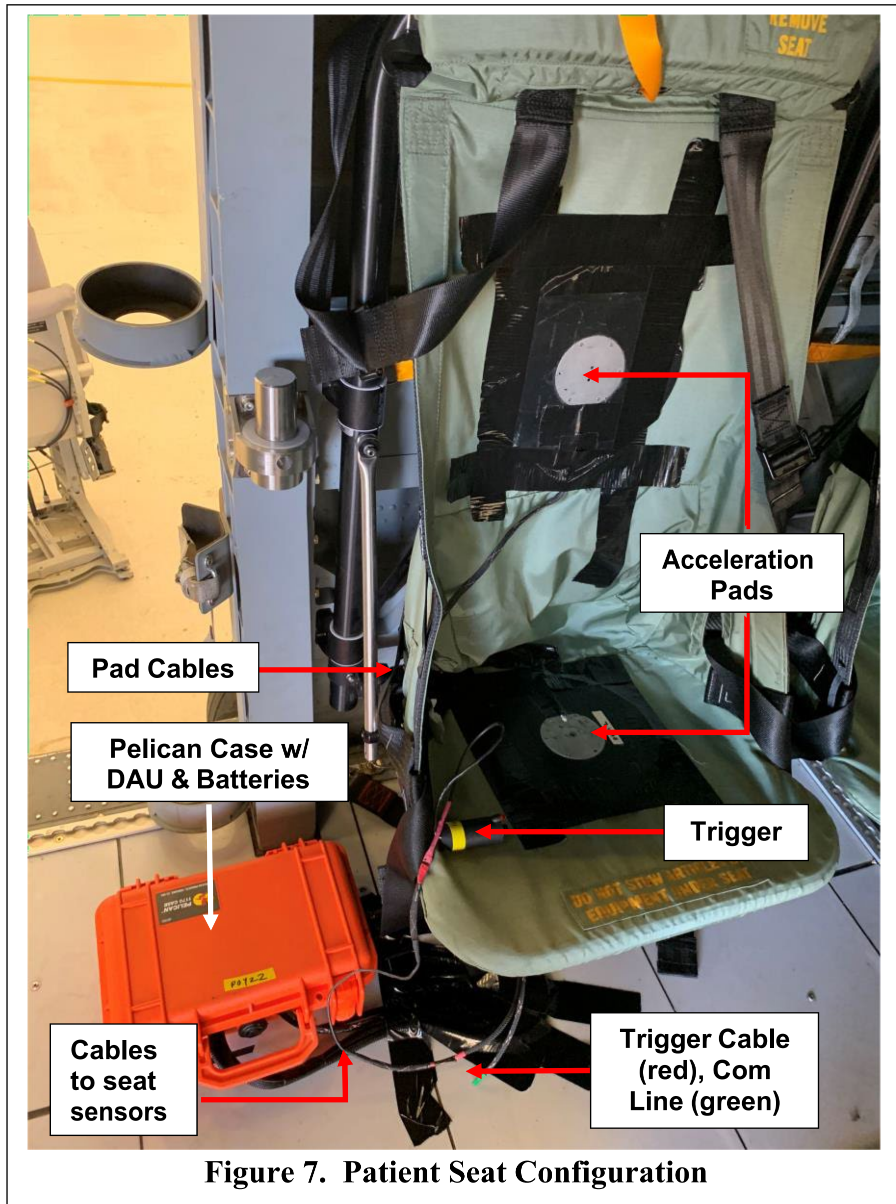

Figure 7. Patient Seat Configuration

3.3 Data Collection, Processing, and Analysis

3.3.1 Data Collection

During each of the two flight tests, triaxial acceleration data were collected at the three patient locations and sites for the flight test conditions listed in the Appendix, Table A-2 Flight Test Conditions and Records. This included taxi, take-off, climb, level flight at several airspeeds, hover, descent, and landing. One AFRL member acted as the test conductor and trigger data

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collection from the three REVER systems once the pilot or copilot indicated that the aircraft was on the specified flight test condition. The test conductor also acted as the seated patient. Multiple data records were collected for several conditions (Table A-2). Data records were collected throughout each flight. The designated test conductor assured that the data records were numbered consecutively in the order they were collected.

Once triggered, data were automatically collected for 20 seconds, low-pass filter with a cutoff frequency of 250 Hz, and digitized at 1024 samples per second. Once the first flight was completed, the laptop was reconnected to each DAU and the time histories for each channel downloaded to the computer. The two litters and respective patients were switched between Tiers 1 and 2. Each DAU was erased and reconfigured to collect data during the second flight. Upon return of the aircraft after the second flight, the laptop was reconnected to the DAU, and the data were downloaded. Table A-2 includes the number of records collected for each flight test condition.

3.3.2 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 percent (%) 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 up to 150 Hz. The constant bandwidth rms acceleration spectra were used to identify 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 between 1 and 80 Hz. The overall unweighted acceleration level, a_{uw}, between 1 and 80 Hz was calculated at each patient location for all measurement sites:

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

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

The assessment of discomfort (comfort reaction) for both the supine and seated patient followed the guidelines in ISO 2631-1: 1997 and the Military Standard (MIL-STD) 1472H, 2020, using the frequency weightings and multiplying factors listed in Table 1 of ISO 2631-1: 1997. It is noted that the X direction of the supine body (spine-chest), denoted as vertical (VX), is in the vertical (Z) direction relative to the vehicle and to the seated patient (Z-axis). The Z direction of the supine body (feet-head), denoted as longitudinal (LZ), corresponds to the longitudinal (X) direction of the aircraft. In addition, all measurement site directions at the seated location were

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relative to the seated patient. Since the seated patient faces sideways, the fore-and-aft direction of these sites (X) coinciding with the patient's X-axis (spine-chest), were oriented along the lateral (Y) direction of the aircraft. The lateral direction of these sites (Y) coinciding with the patient's Y-axis (side-to-side), were oriented along the longitudinal (X) direction of the aircraft.

The overall weighted rms acceleration level, a_w, was calculated between 1 and 80 Hz in each of the three orthogonal axes relative to the coordinate system defined for the supine and seated occupants:

$$a_w = \left[\sum_i W_{il}^2 \, a_{rmsi}^2\right]^{1/2} \quad (2)$$

where l represents the particular frequency weighting (d, k, c, or j) depending on the location and direction, i represents the *ith* frequency component, and a_{rmsi} is the measured one-third octave acceleration level at center frequency i. While ISO 2631-1 does not use the weighted back interface accelerations for assessing comfort of the supine occupant, 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 for the supine occupant, but does not provide specific guidance on comfort based on the head weighted value. In this study, the lateral (Y) and longitudinal (LZ), or horizontal, head accelerations for the supine patient were also weighted using W_d. For assessing comfort reaction, the point vibration total value (*pVTV*) was calculated as the vector sum of the overall weighted VX, Y, and LZ accelerations for the litter patient, and the X, Y, and Z accelerations for the seated patient, after applying the appropriate multiplying factors:

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

The overall vibration total value (*oVTV)* for the seated patient was calculated as the vector sum of the seat pan and seat back *pVTVs*, as defined in ISO 2631-1. The *pVTVs* and *oVTV*s 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".

The assessment of health risk, in accordance with the ISO 2631-1, is based on repeated daily exposures to occupational vibration. The assessment is primarily focused on the seated worker or occupant. Patients being transported for medical care are not exposed to vibration on a daily basis. Therefore, the assessment of health risk was not appropriate for the transported patient.

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4.0 RESULTS

All figures and tables referred to in this section are located in the Appendix. A review of the time history data indicated that certain data channels were corrupted for most of the collected data records. Other cases showed that specific records included corrupted data in one or more channels. This was reflected in the notably large standard deviations in the mean unweighted and weighted acceleration levels for the specific flight test condition. Records containing corrupted data were eliminated from the analysis. In addition, if the corrupted channel was associated with the calculation of the p*VTV* and/or o*VTV*, these calculations were eliminated from the analysis. Table A-2 summarizes those records that were eliminated.

It is noted that the seated subject is oriented 90 degrees from the longitudinal axis of the aircraft. All measurements at the seat location are relative to the subject coordinate system. Therefore, the fore-and-aft (X) direction of the seat and subject are oriented in the lateral direction of the aircraft, while the lateral (Y) direction of the seat and subject are oriented along the longitudinal axis of the aircraft.

4.1 Characteristics of the UH-60L Acceleration Spectra

Figures A-1, A-2, and A-3 illustrate sample multi-axis rms acceleration spectra between 1 and 80 Hz from Flight 2 during level flight at 100 Knots Calibrated Airspeed (KCAS) at the targeted measurement sites for the Tier 1 litter, Tier 2 litter, and left seat, respectively. In particular, the litter data showed a distinct peak, primarily in the vertical (VX) direction, around 4.5 Hz that was associated with the rotor speed or propeller rotation frequency (PRF) of the aircraft. All measurement sites showed a distinct peak between 17 and 17.5 Hz of variable magnitude and direction that was associated with the blade passage frequency (BPF) of the aircraft (Smith, et al., 2019). Additional peaks of variable magnitudes and direction were also observed at multiples of the BPF. Other peaks were most likely the result of excited resonance behavior in the litter system and seat system structures.

4.2 Overall Unweighted Acceleration Levels

The overall unweighted accelerations, calculated between 1 and 80 Hz in accordance with Equation 1, were used to visualize the vibration levels among the flight test conditions and in the three directions. It is cautioned that the summary provided below on the unweighted overall accelerations are observations and have not been statistically evaluated for significant effects except where noted for the overall unweighted level flight vibration levels.

4.2.1 Litter Patients

Figures A-4 and A-7 illustrate the mean overall unweighted accelerations ± one standard deviation at the pelvis interface, back interface, and head for all flight test conditions at Tier 1 during Flights 1 and 2, respectively. Figures A-5 and A-8 illustrate these results at Tier 2 during Flights 1 and 2, respectively. At the Tier 1 litter pelvis and back interfaces, the highest vibration levels tended to occur in the lateral (Y) direction, while the lowest vibration levels tended to occur in the vertical (VX) direction during both flights (Pelvis VX data bad for Flight 1). This was particularly consistent for TASK 1052, which included level flight. Larger variations in the

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data were noted during TASK 1058, which included approaches to Out of Ground Effect (OGE) and In Ground Effect (IGE) hover and to ground. At the Tier 1 head measurement sites, the overall unweighted vibration levels tended to be relatively lower as compared to the interfaces, and more similar among the three directions during both flights. Although not illustrated, these tendencies were also observed at the chest measurement sites. At the Tier 2 litter pelvis and back interfaces, the lowest vibration levels tended to occur in the vertical (VX) direction, as was shown for Tier 1, for both flights. However, at the Tier 2 litter pelvis and back interfaces, the highest vibration levels tended to occur in the longitudinal (LZ) direction for both flights, with the notable exception of most flight conditions associated with TASK 1052. With TASK 1052 during Flight 2, the Tier 2 interfaces showed the highest levels occurring in the lateral (Y) direction, similar to the trends observed at Tier 1. Interestingly, the highest and most dramatic litter interface vibration levels observed among all of the flight conditions occurred in the longitudinal (LZ) direction for the steep rate turn at 60 degrees. This flight condition was only performed during Flight 2. As was observed at Tier 1, the head and chest overall unweighted vibration levels tended to be relatively lower as compared to the interfaces, and more similar among the three directions during both flights. In addition, during level flight, the higher airspeeds tended to show higher overall levels. This was more noticeable at Tier 2, particularly at the 120 and 145 KCAS level flight conditions. It is noted that the patient/litters were switched between Flights 1 and 2, i.e., Patient 1 was located at Tier 1 during Flight 1, and relocated to Tier 2 during Flight 2.

Figures A-10 and A-11 include the mean overall unweighted accelerations ± one standard deviation for level flight at the four airspeeds at the support platform, pelvis interface, and back interface for both flights at the Tier 1 and Tier 2 litter locations, respectively. The Repeated Measures Analysis of Variance (RM ANOVA) and Bonferroni t-Test were used to determine statistical significance of differences in the overall unweighted levels with respect to direction and tier location.

Table A-3 lists the statistical findings with regard to direction effects during level flight. With reference to Figure A-10 and Table A-3 for the Tier 1 litter location, the support platform showed that the highest overall unweighted accelerations during level flight occurred in the vertical (VX) direction, while the lowest overall unweighted level occurred in the longitudinal (LZ) direction for both flights (probability value (P) < 0.05). In contrast, at the Tier 1 pelvis and back interfaces, the highest overall unweighted level flight accelerations occurred in the lateral (Y) direction, while the lowest overall levels occurred in the vertical (VX) direction for both flights (note missing data for pelvis during Flight 1) ($P < 0.05$). With reference to Figure A-11 and Table A-3 for the Tier 2 litter location, the support platform, as with Tier 1, showed that the higher overall unweighted accelerations during level flight occurred in the vertical (VX) direction for both flights ($P < 0.05$). There were no significant differences between the support platform overall levels in the lateral (Y) as compared to the longitudinal (LZ) directions at Tier 2. At the Tier 2 pelvis and back interfaces, the highest overall interface levels occurred in the longitudinal (LZ) direction during Flight 1, while the highest levels occurred in the lateral (Y) direction during Flight 2 ($P < 0.05$). The lowest levels still occurred in the vertical (VX) direction ($P < 0.05$), similar to the results for Tier 1.

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Table A-4 lists the statistical findings with regard to tier effects during level flight. With reference to Figures A-10 and A-11, and Table A-4, the overall unweighted accelerations at the support platform during level flight were higher at Tier 2 as compared to Tier 1 in the longitudinal (LZ) and vertical (VX) directions, but higher at Tier 1 as compared to Tier 2 in the lateral (Y) direction for both flights ($P < 0.05$). Both the pelvis and back interfaces showed higher overall unweighted level flight accelerations at Tier 2 as compared to Tier 1 in the longitudinal (LZ) direction for both flights ($P < 0.05$). Both interfaces showed higher overall unweighted level flight accelerations at Tier 2 as compared to Tier 1 in all three directions during Flight 2 ($P < 0.05$). However, during Flight 1, the overall unweighted level flight accelerations at the pelvis interface in the lateral (Y) direction were higher at Tier 1 ($P < 0.05$), although relatively similar when comparing Figure A-10 to A-11. The vibration levels were similar at the back interface for the two tiers (Table A-4).

4.2.2 Seated Patient

Figures A-6 and A-9 illustrate the mean overall unweighted accelerations ± one standard deviation at the seat support bar, seat pan interface, and seat back interface for all flight test conditions during Flights 1 and 2, respectively. The overall unweighted vibration levels tended to be the highest in the vertical (Z) direction at these three measurement sites. The one exception was the similarity among the accelerations in the three directions at the seat pan interface for TASK 1052, which included level flight. For those flight conditions associated with TASK 1058, which included approaches, the higher overall vertical (Z) levels were quite noticeable, with relatively large variability among the data records.

Figure A-12 includes the mean overall unweighted level flight accelerations ± one standard deviation at the seat support bar, seat pan interface, and seat back interface for both flights. The RM ANOVA and Bonferroni t-Test were used to determine statistical significance.

Table A-5 lists the statistical findings with regard to direction effects at each of the seat measurement sites. The seat support bar and seat back interface produced the highest overall unweighted vibration levels in the vertical (Z) direction ($P < 0.05$) during level flight for both flights, as illustrated in Figure A-12. The difference was the most dramatic at the seat back, where the lowest overall levels occurred in the fore-and-aft (X) direction (lateral (Y) direction of the aircraft) ($P < 0.05$). In contrast, at the seat pan, the highest overall levels occurred in the lateral (Y) direction (fore-and-aft or longitudinal direction of the aircraft) ($P < 0.05$). As depicted in Figure A-12, these differences were not as dramatic as those occurring at the seat back.

4.3 Overall Weighted Accelerations and Vibration Total Values (p*VTV*s, o*VTV*s) for Comfort Assessment

The overall weighted acceleration levels, p*VTV*s, and o*VTV*s (seat only) were calculated in accordance with Equations 2 and 3.

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4.3.1 Litter Patients

Figures A-10 and A-11 include the overall weighed accelerations ± one standard deviation for level flight in the three directions at the pelvis and back interfaces during Flight 1 and Flight 2, respectively. In contrast to the overall unweighted acceleration levels, the highest overall weighted interface vibration levels occurred in the vertical (VX) direction. Once weighted, the horizontal levels were notably reduced compared to the unweighted levels.

Figures A-13 and A-14 illustrate the mean vibration total values (*VTV*s) ± one standard deviation at the litter patient pelvis and back interfaces for Tiers 1 and 2 for all flight test conditions during Flight 1 and Flight 2, respectively. Included are the comfort reaction regions defined in the ISO 2631-1. The figures show that, at the two litter locations, the interface vibration would be primarily considered "a little uncomfortable", with some exceptions. Of particular interest were those exceptions occurring during TASK 1052, which included level flight and the steep rate turn at 60 degrees (Flight 2 only). At Tier 1, none of the records associated with level flight showed pelvis interface p*VTV*s that exceeded 0.5 meters per second squared (ms^{-2}) rms (data available for Flight 2 only). At Tier 1 during Flight 1, all 10 back interface records associated with level flight at 145 KCAS showed p*VTV*s that exceeded 0.5 ms^{-2} rms, and would be considered "fairly uncomfortable". At Tier 2 during Flight 1, 5 of the 10 back interface records during level flight at 120 KCAS showed p*VTVs* that exceeded 0.5 ms^{-2} rms. Three (3) of the 10 pelvis interface records and 9 of the 10 back interface records during level flight at 145 KCAS showed p*VTV*s that exceeded 0.5 ms^{-2} rms. These exposures would be considered "fairly uncomfortable". At Tier 2 during Flight 2, all 10 back interface records at 120 KCAS showed p*VTV*s that exceeded 0.5 ms^{-2} rms. Two (2) of the 10 pelvis interface records and all 10 back interface records at 145 KCAS showed p*VTV*s that exceeded 0.5 ms^{-2} rms. These exposures would also be considered "fairly uncomfortable" as defined in ISO 2631-1. It is noted that, during the steep rate turn at 60 degrees, 1 of the 3 pelvis interface p*VTV* records exceeded 0.8 ms^{-2} rms and would be considered "uncomfortable".

Although the ISO 2631-1 provides a frequency weighting, W_j, for vertical head vibration in the recumbent or supine posture, it does not provide guidance on comfort reaction. The results of this study did show that, at Tier 1, 1 of 10 overall weighted vertical head records during Flight 1, and 6 of 10 records during Flight 2 exceeded 0.5 ms^{-2} rms. At Tier 2, 8 of 8 records during Flight 1 and all 10 records during Flight 2 exceeded 0.5 ms^{-2} rms.

4.3.2 Seated Patient

Figure A-12 includes the overall weighted acceleration levels ± one standard deviation in the three directions for level flight at the seat pan and seat back interfaces. In contrast to the unweighted levels at the seat pan, which tended to be similar among the three directions, the overall weighted accelerations were notably the highest in the vertical (VX) direction. The seat pan weighted levels in the horizontal (X, Y) directions were notably reduced compared to the unweighted levels. In contrast to the notably higher overall unweighted vertical (Z) accelerations at the seat back, the overall weighted levels were more similar among all three directions.

Figures 13 and 14 show that, at the seat location, the vibration at the seat back interface would be considered "not uncomfortable" for most flight conditions. However, the vibration at the seat pan interface ranged from being "a little uncomfortable" to even "very uncomfortable", the

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higher levels of discomfort associated with TASK 1058, which included approaches. These results were also reflected in the o*VTV*s. During Flight 1, 7 of 10 seat pan p*VTV* records and 6 of 10 o*VTV* records at 120 KCAS exceeded 0.5 ms^{-2} rms, and would be considered “fairly uncomfortable” in accordance with ISO 2631-1. The remaining 3 p*VTV* records and 4 o*VTV* record exceeded 0.8 ms^{-2} rms and entered the “uncomfortable” region. During Flight 1, all 10 records showed p*VTV*s and o*VTV*s records at 145 KCAS exceeding 0.5 ms^{-2} rms would be considered “fairly uncomfortable”. During Flight 2, all 10 p*VTV* records and 9 of the 10 o*VTV* records at 120 KCAS exceeded 0.5 ms^{-2} rms and would be considered “fairly uncomfortable”. One (1) o*VTV* record exceeded 0.8 and entered the “uncomfortable” region. All 10 p*VTV* records and 7 of the 10 o*VTV* records at 145 KCAS exceeded 0.5 ms^{-2} rms and would be considered “fairly uncomfortable”. Three (3) of the 10 o*VTV* records exceeded 0.8 entered the “uncomfortable” region.

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5.0 DISCUSSION AND CONCLUSIONS

This project sought to collect and characterize vibration transmitted to litter patients and seated patients during a typical AE transport scenario aboard the UH-60L configured with the IMMSS. Triaxial accelerations were collected at the interfaces between the patient and litter or seated surfaces, and at selected anatomical sites. Two litter tiers were included for the supine or recumbent patient. Three subjects participated in the flight tests. Two flight tests were conducted on different days. It was expected that subject posture and anthropometry could have an influence on the measurement of acceleration. In addition, it was expected that certain weather conditions and/or flight conditions could also affect the accelerations transmitted to the subject patients. During the first flight, Subject 1 was located at Tier 1 and Subject 2 was located at Tier 2. During the second flight, Subject 1 was located at Tier 2 and Subject 2 was located at Tier 1. It is noted that the flight test conditions included in this study were similar to those conditions included in a previous study that collected aircrew vibration data during typical operations (Smith, S.D. et al., 2019). While it is not known if any of these flight conditions would be avoided when transporting injured patients, it is assumed that the pilot would attempt to avoid the more extreme conditions (i.e., steep rate turn at 60 degrees).

The acceleration spectra revealed that the contribution of the UH-60L propulsion system to the vibration entering the patients was similar to that observed for the vibration entering the aircrew in the previous study (Smith, S.D. et., 2019). First, at the litter locations, notable peaks were observed around the PRF (4.5 Hz) and around the BPF (17.5 Hz). The magnitude of these peaks depended on the direction. The multiple peaks observed beyond the BPF, particularly at the litter/patient interfaces, would influence the overall unweighted accelerations, but have less influence on the overall weighted accelerations due to the ISO 2631-1 associated frequency weightings. At the head and chest, the vibration was quite damped beyond the BPF. For the seated patient, the peak associated with the PRF was less noticeable.

The overall unweighted accelerations measured during level flight at the litter interfaces, as well as the statistical findings, revealed notable trends in the vibration entering the patients. As depicted in Figures A-12 and A-13, and shown in Table A-3, both tiers showed that the unweighted horizontal (Y, LZ) vibration at the interfaces was significantly higher as compared to the vertical (VX) vibration, in contrast to the significantly higher vertical (VX) vibration observed at the litter support plates. It appeared that the relatively high vertical (VX) motions observed at the center support platform site did not have a major influence on the vertical (VX) motions at the pelvis and back interfaces. This may have been due to the attachment of the litters to the platforms at the four corners, as illustrated in Figure 2.

For the statistical analysis comparing the effects of tier, it was assumed that the vibration levels had similar characteristics between the two flights. The similarity in the overall level flight accelerations at the center support plate for the two patients at Tier 1 (Figure A-12) during both flights, and the tendency for similarity at Tier 2 during both flights (Figure A-13), support this assumption. In addition, Tier 2 showed significantly higher vertical (Z) vibration as compared to Tier 1. Both patients also showed similar overall unweighted acceleration levels at the litter interfaces and similar directional effects for Tier 1 (Figure A-12, Table A-3) with the highest vibration levels occurring in the lateral (Y) direction during both flights. This was not the case at

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Tier 2 where, during Flight 1, Patient 2 showed the highest overall unweighted vibration in the longitudinal (LZ) direction, while during Flight 2, Patient 1 showed the highest in the lateral (Y) direction, similar to the trends observed at Tier 1 (Figure A-13, Table A-3). While the mass of Patient 1 was approximately 92 Kg, the mass of Patient 2 was approximately 70 Kg. It was not clear how the differences in mass and weight distribution may have affected these results at Tier 2, particularly since they were not observed at Tier 1. Interestingly, during Flight 2, where both tiers showed the highest interface vibration in the lateral (Y) direction, all three directions showed significantly higher vibration levels at Tier 2 as compared to Tier 1. During Flight 1, Tier 1 showed either higher lateral (Y) vibration (pelvis), or similar lateral (Y) vibration as compared to Tier 2. Figures A-12 and A-13 show that these differences were not dramatic. As shown in Figure 3, Tier 2 was cantilevered, which may have influenced the observed higher motions to some extent. In summary, these results do suggest that to minimize patient vibration, it is best to position the patient at Tier 1.

The levels of vibration transmitted to the seated patient at the interfaces appeared to be relatively similar to the levels transmitted to the litter patients at the interfaces with some exceptions. In addition to the relatively high levels of vertical (Z) vibration occurring at all seat measurement sites for TASK 1058 (approaches), the vertical (Z) vibration at the seat back was also quite substantial for most of the flight conditions. There was the concern as to how well the patient was coupled to the cloth seat back. In addition, the seat pan was cantilevered and constructed of a thin metal plate covered with cloth (Figure 7), which contributed to a very hard seat surface.

It is noteworthy that the weighting of the vibration in accordance with ISO 2631-1 reduced the contribution of the higher unweighted horizontal (Y, LZ) vibration observed at the litters to very low values compared to the vertical (VX) vibration, as depicted in Figures A-10 and A-11. In addition, the weighted vertical (Z) vibration at the seat interfaces tended to be higher at the seat pan and lower at the seat back as compared to the litter interfaces, with more notable contributions in the seat back fore-and-aft (X) (lateral (Y) relative to aircraft and litters) vibration. Although relatively high levels of vertical (Z) vibration were observed at the seat back, the ISO multiplying factors for assessing seat back comfort had an influence in reducing the vertical (Z) contribution.

Based on the overall weighted acceleration levels, the ISO comfort assessment of the litter vibration indicated that, except in the extreme case of the steep rate turn at 60 degrees, most of the flight test conditions evaluated in this study exposed the litter patients to vibration that was considered primarily “a little uncomfortable”. However, the level flight conditions at the higher airspeeds of 120 and 145 KCAS exposed the patients to vibration levels at the back interface that would be considered “fairly uncomfortable”, particularly if the patient was located at Tier 2. This further supports the recommendation to locate the most seriously injured at Tier 1. Likewise, for the seated patient, the exposures were considered “fairly uncomfortable” and even “very uncomfortable” at the higher airspeeds, being primarily driven by the seat pan weighted levels. The seated subject was also exposed to “uncomfortable” and “very uncomfortable” vibration during hover and approaches. Aeromedical evacuation via the UH-60L may be the first extraction point for the injured patient, or may proceed initial transport via a ground vehicle. Depending on the duration of the air transport to a medical facility or another transport vehicle, it is expected that the longest exposures would be during level flight.

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It is strongly emphasized that the comfort reactions defined in ISO 2631-1 are based on the reactions expected of relatively healthy occupants during public transport. It is speculated that most occupants of public transport are in a seated posture and not the supine posture, and certainly not suffering any traumatic injury. While the standard litter used in this project did not include a cushioned mat, it is recommended that this be done during actual medical transport, if not already, for improving the injured patient's comfort. In addition, for those patients suffering head or spine injury, it is advisable to include additional restraint to restrict upper torso motion. It is expected that, during medical transport, only minimally injured patients would be placed in the seated location. Given the comfort reactions revealed in this project, it is recommended that some type of cushion be placed between the buttocks and seat pan surface to improve seat patient comfort.

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LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

711 HPW	711 Human Performance Wing
AE	Aeromedical Evacuation
AFRL	Air Force Research Laboratory
AFMS	Air Force Medical Service
amp	Ampere
ANOVA	Analysis of Variance
BPF	Blade Passage Frequency
CBDN	Collaborative Biomechanics Data Network
DAU	Data Acquisition Unit
ft	Feet
Hz	Hertz (cycles per second)
IMMSS	Interim Medevac Mission Support System
ISO	International Organization for Standardization
MD ARNG	Maryland Army National Guard
MIL-STD	Military Standard
P	Probability Value
PRF	Propeller Rotation Frequency
RM ANOVA	Repeated Measures Analysis of Variance
REVER	Remote Vibration Environment Recorder
RH	Airman Systems Directorate
VTV	Vibration Total Values
%	percent
ms^{-2}	Meters per Second Squared
rms	Root-Mean-Square
a_{rms}	Acceleration Root-Mean-Square
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)

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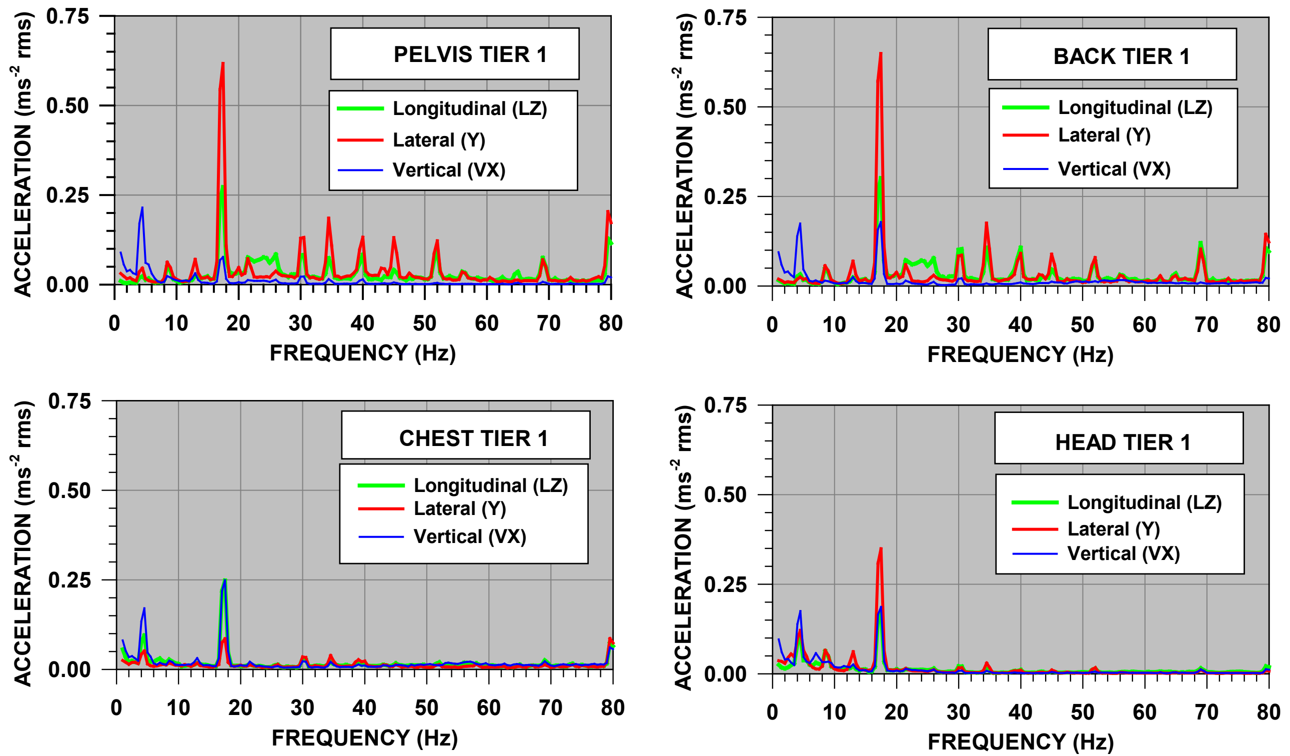

Figure A-1. Sample RMS Spectra: Flight 2, Litter Tier 1, Level Flight 100 KCAS

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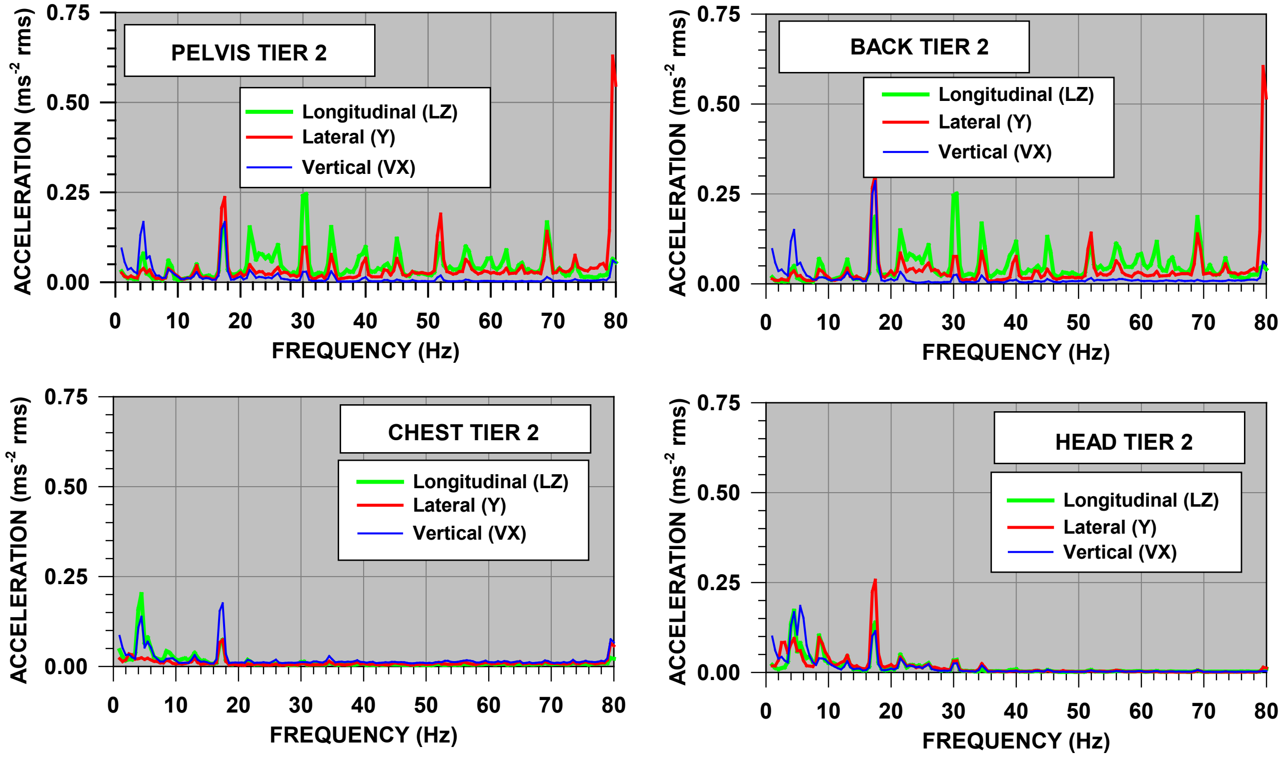

Figure A-2. Sample RMS Spectra: Flight 2, Litter Tier 2, Level Flight 100 KCAS

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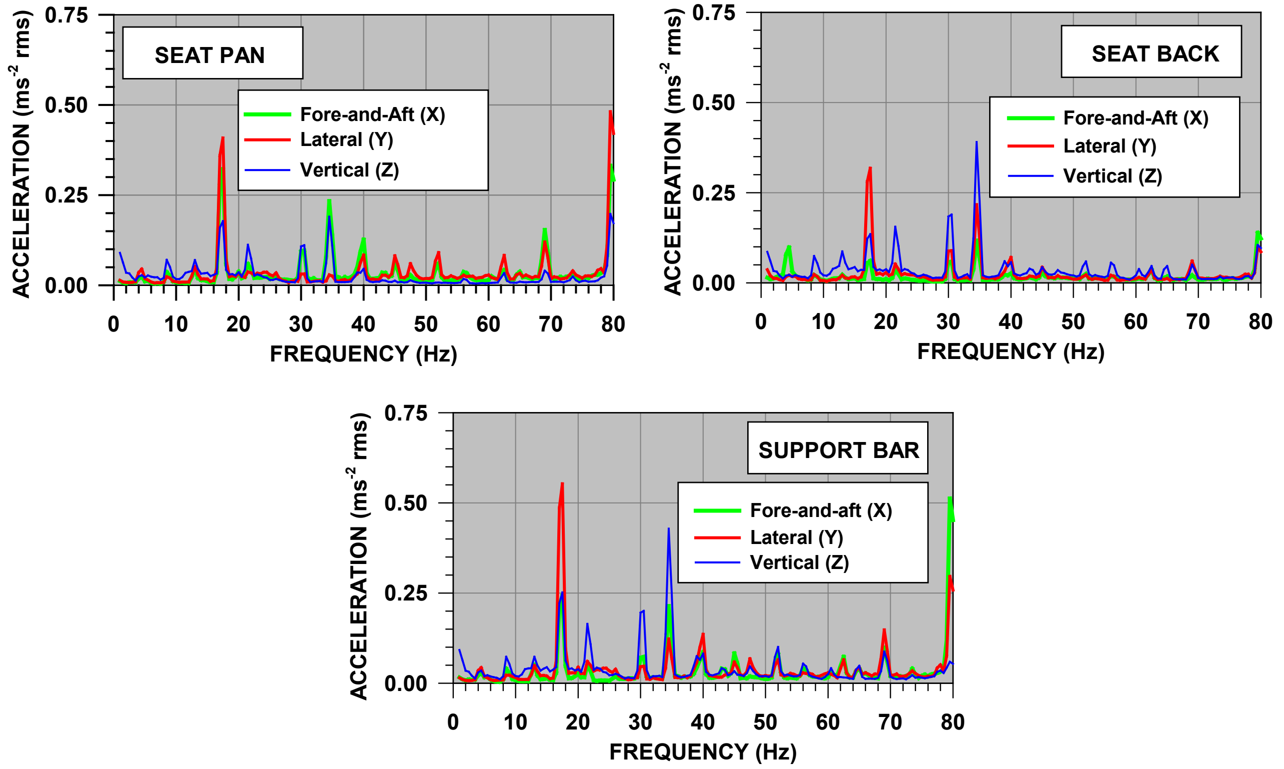

Figure A-3. Sample RMS Spectra: Flight 2, Left Seat, Level Flight 100 KCAS

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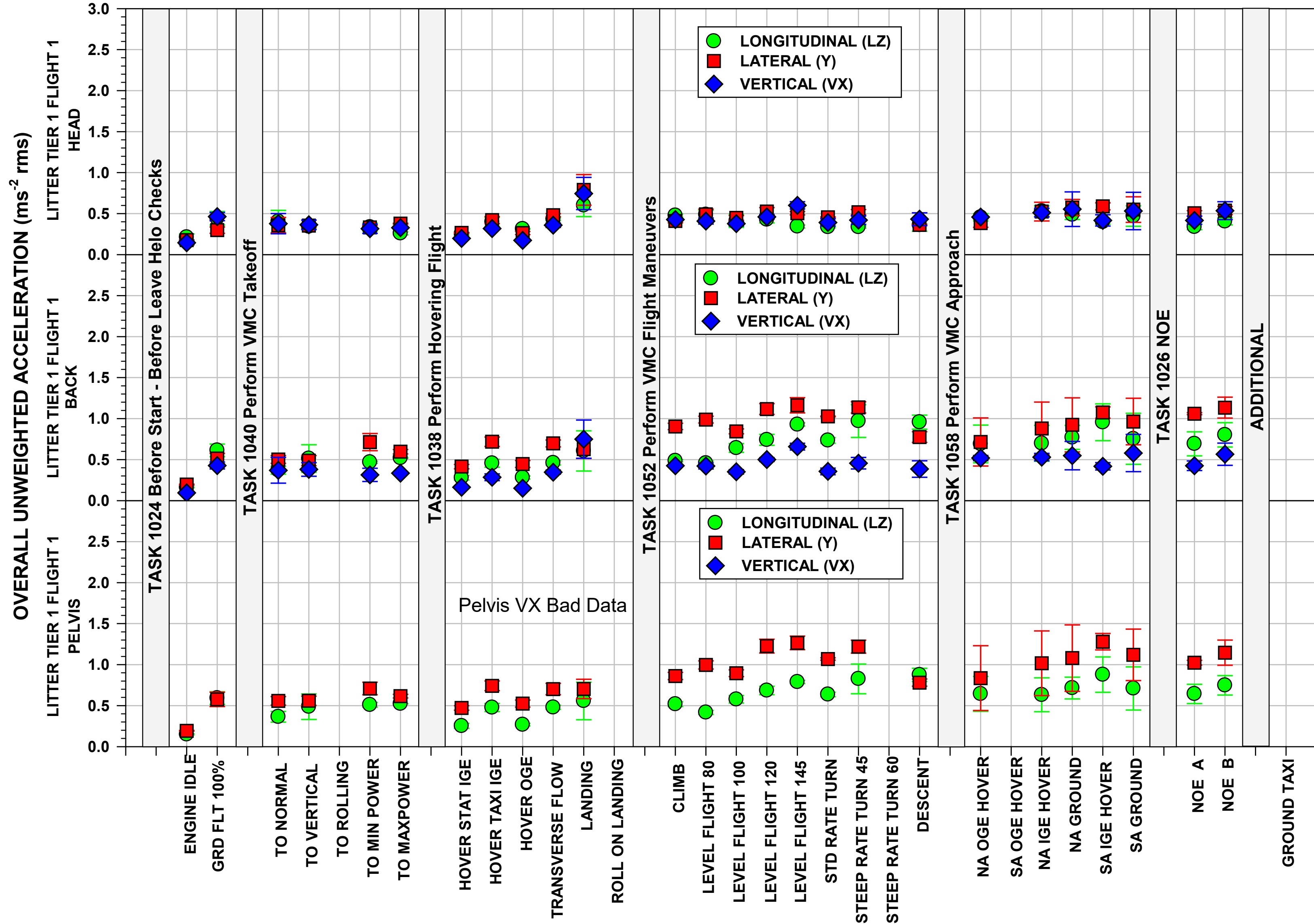

Figure A-4. Mean Overall Unweighted Acceleration ± One Standard Deviation – Litter Tier 1 Flight 1 (Patient 1)

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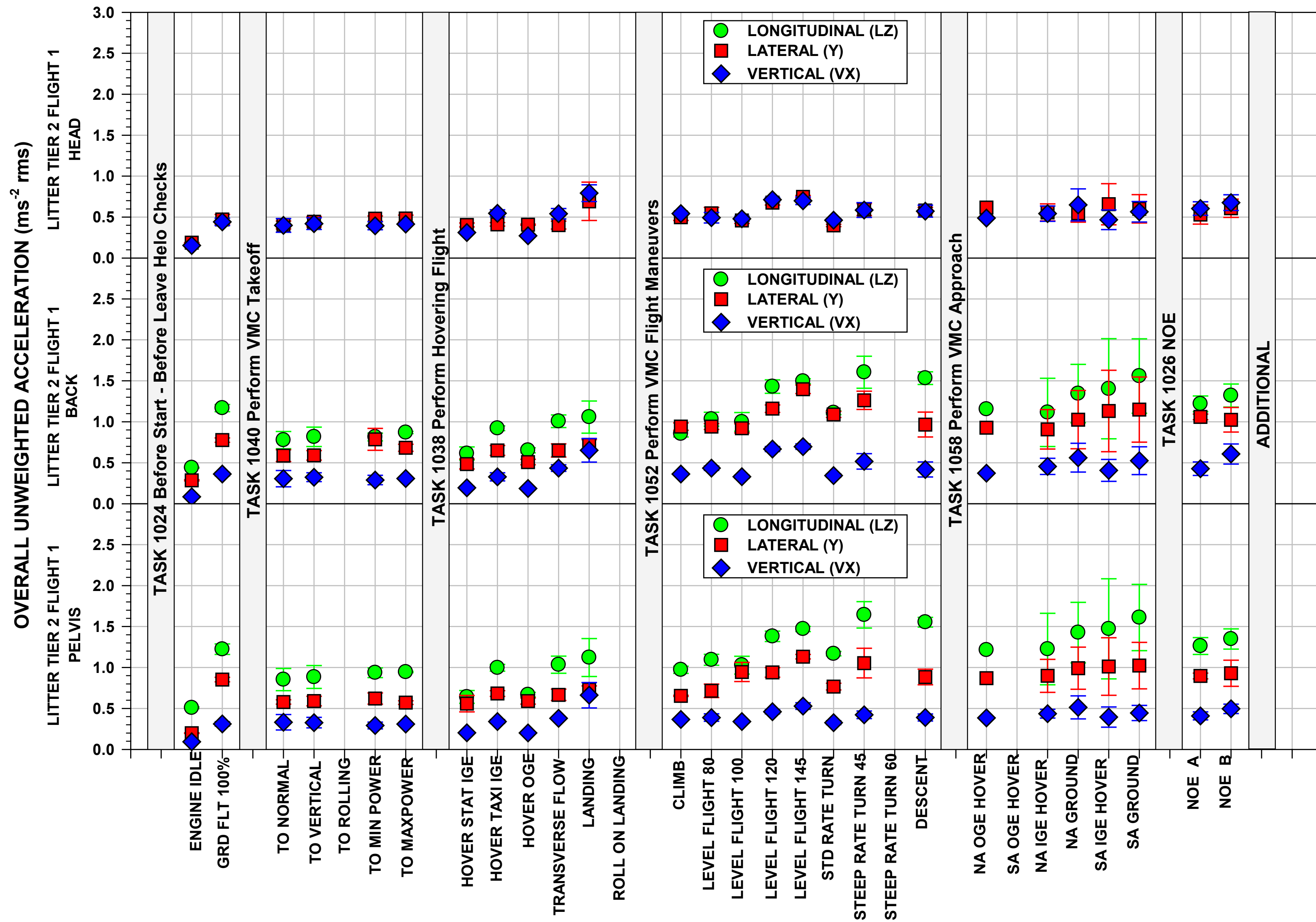

Figure A-5. Mean Overall Unweighted Acceleration ± One Standard Deviation – Litter Tier 2 Flight 1 (Patient 2)

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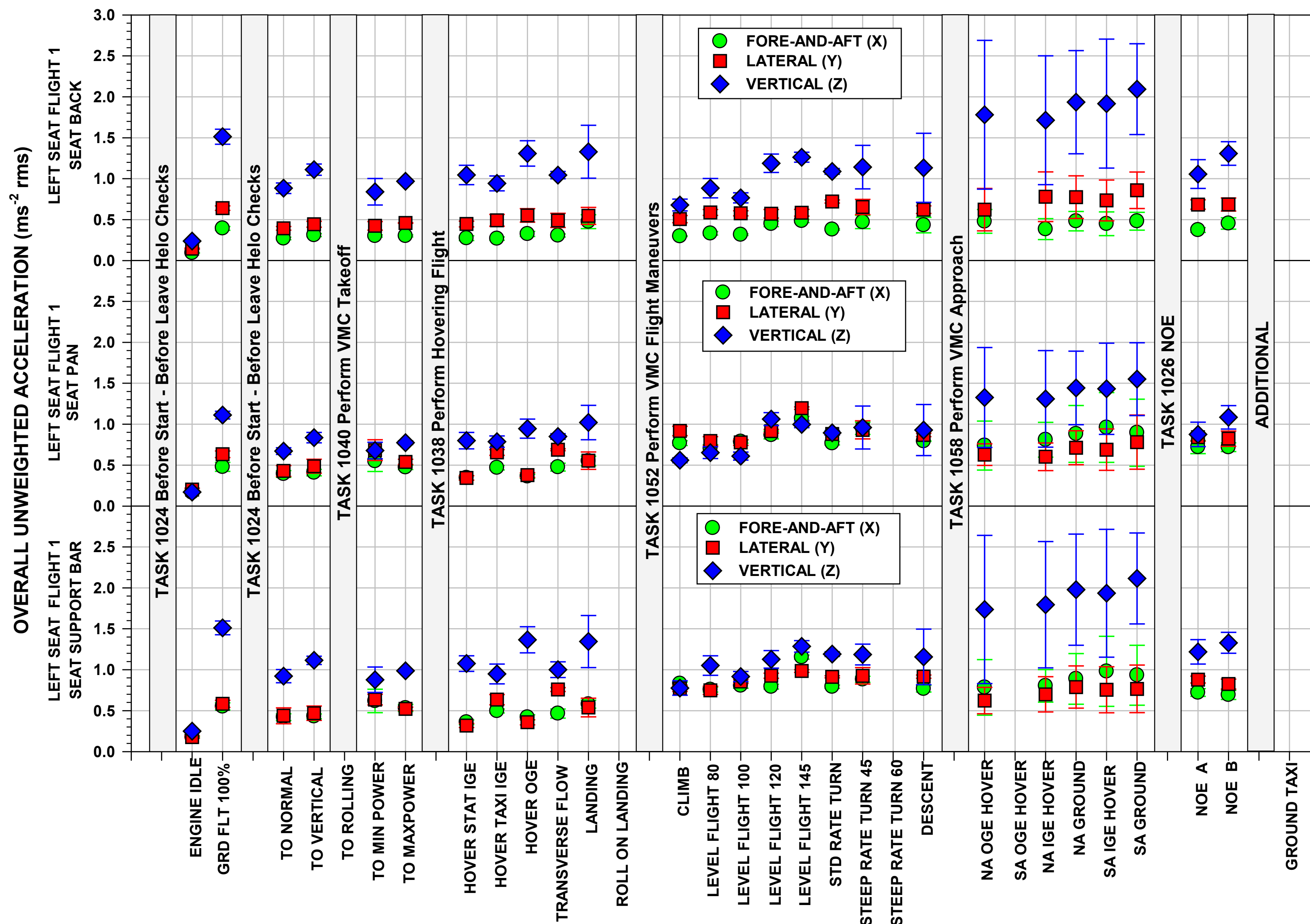

Figure A-6. Mean Overall Unweighted Acceleration ± One Standard Deviation – Seat Flight 1 (Patient 3)

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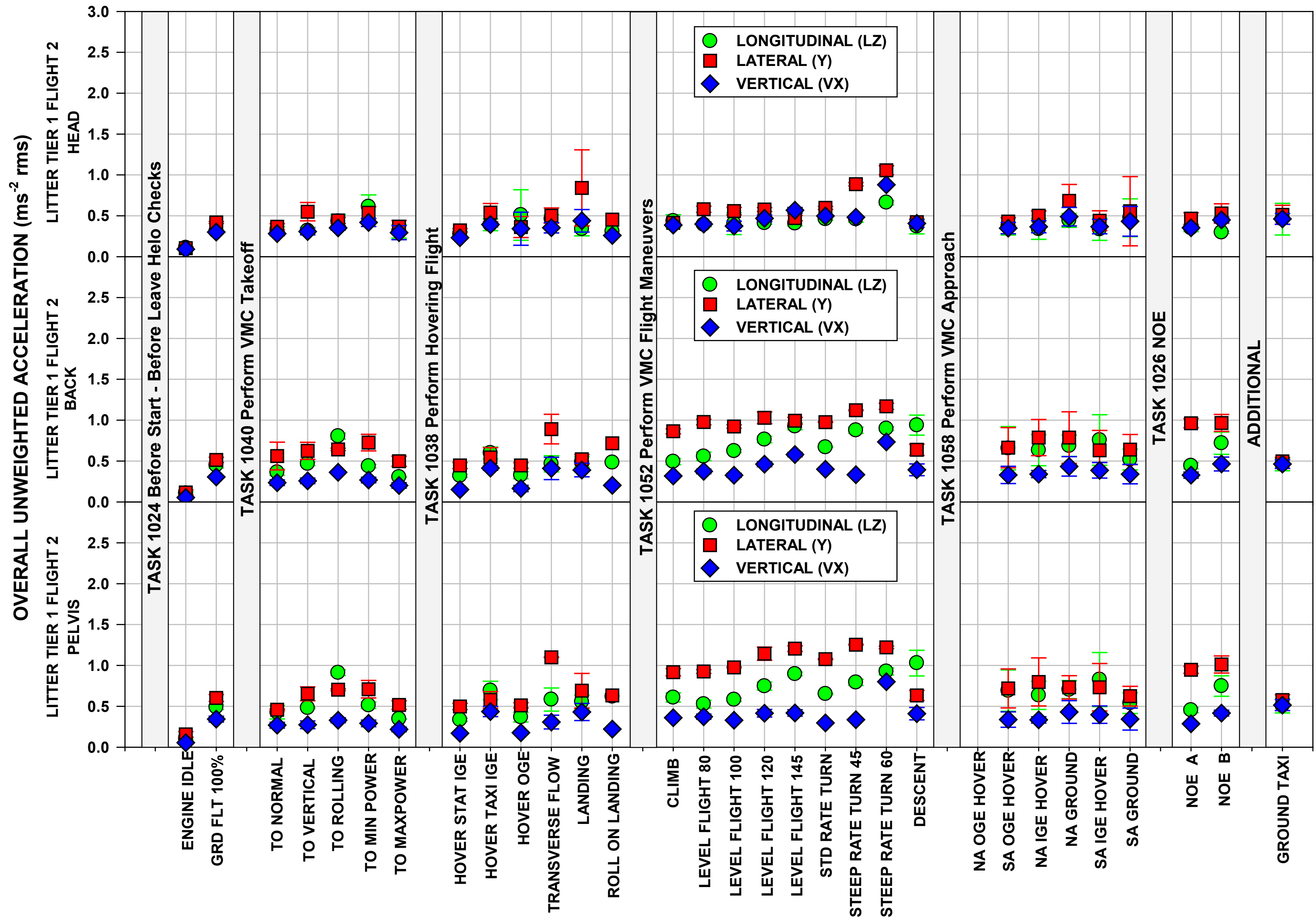

Figure A-7. Mean Overall Unweighted Acceleration ± One Standard Deviation – Litter Tier 1 Flight 2 (Patient 2)

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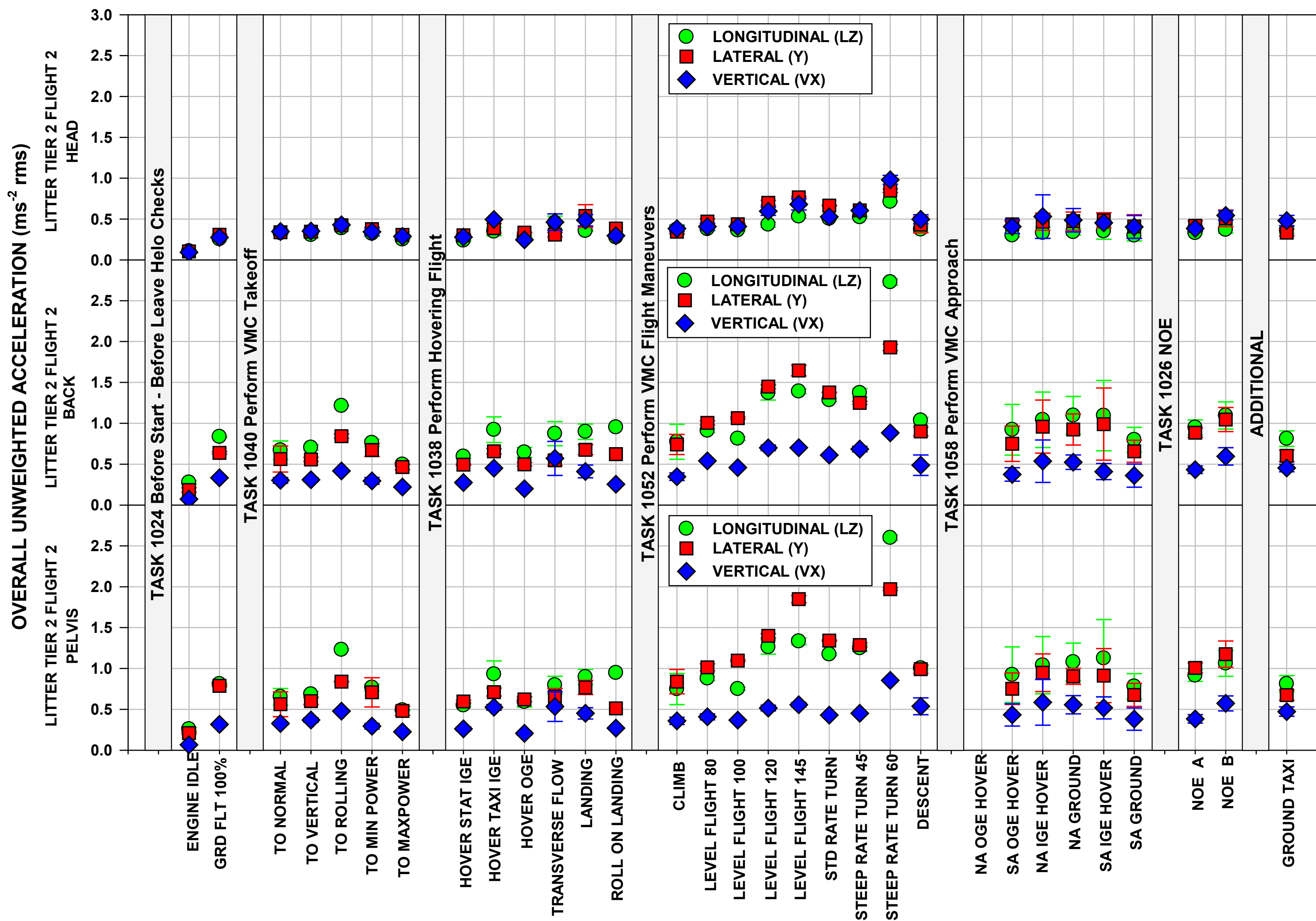

Figure A-8. Mean Overall Unweighted Acceleration ± One Standard Deviation – Litter Tier 2 Flight 2 (Patient 1)

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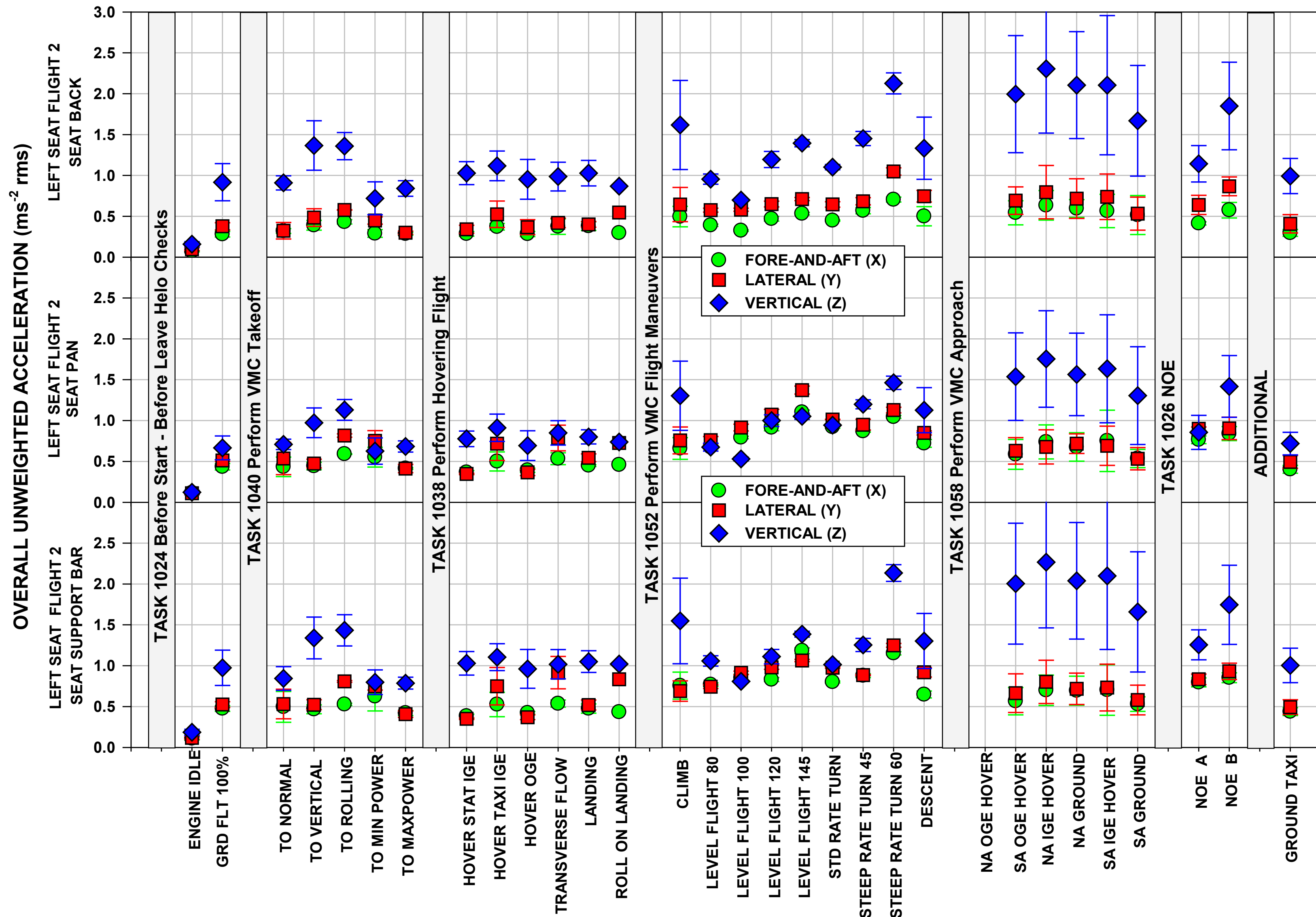

Figure A-9. Mean Overall Unweighted Acceleration ± One Standard Deviation – Seat Flight 2 (Patient 3)

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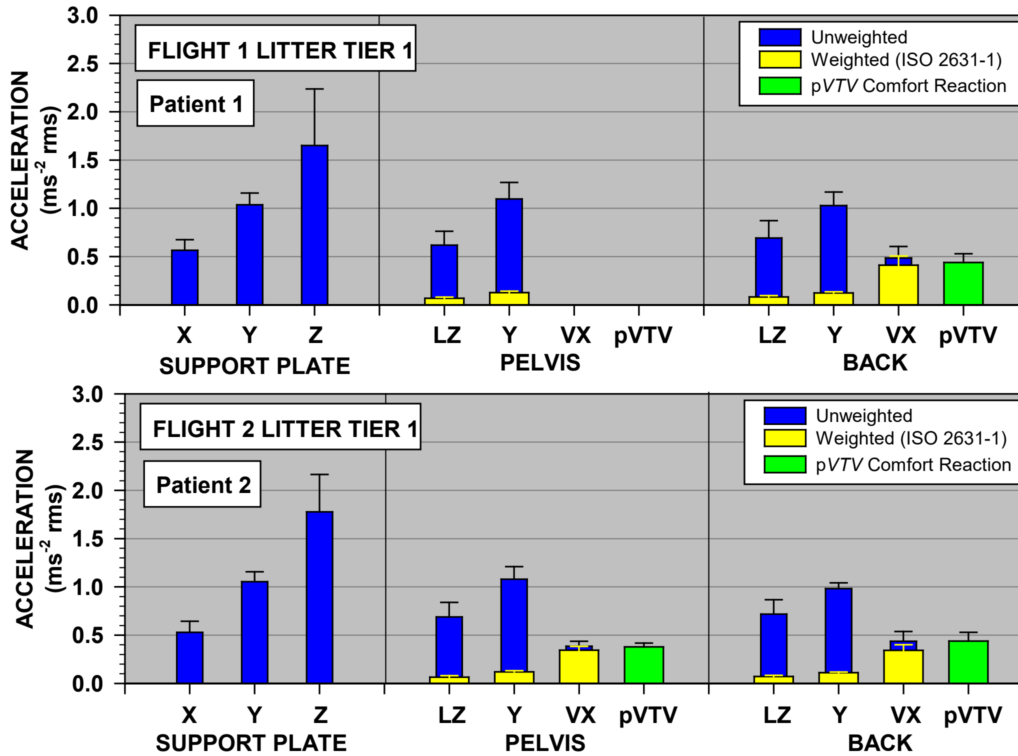

Figure A-10. Mean Unweighted and Weighted Level Flight Overall Accelerations, pVTVs ± One Standard Deviation – Litter Tier 1

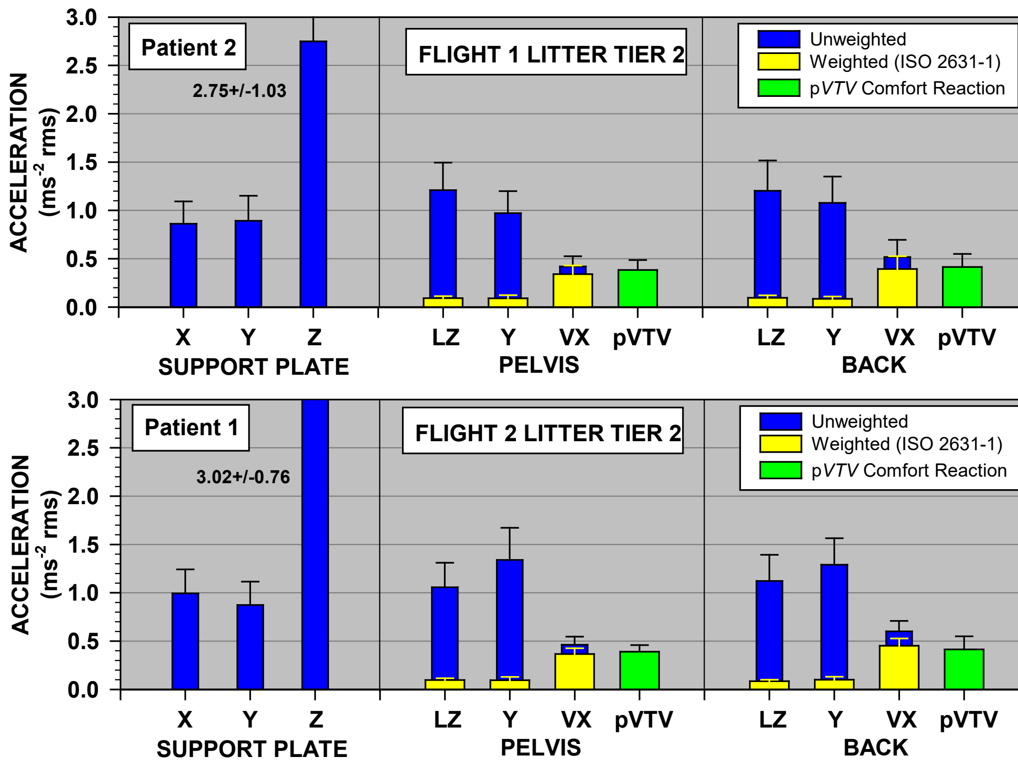

Figure A-11. Mean Unweighted and Weighted Level Flight Overall Accelerations, pVTVs ± One Standard Deviation – Litter Tier 2

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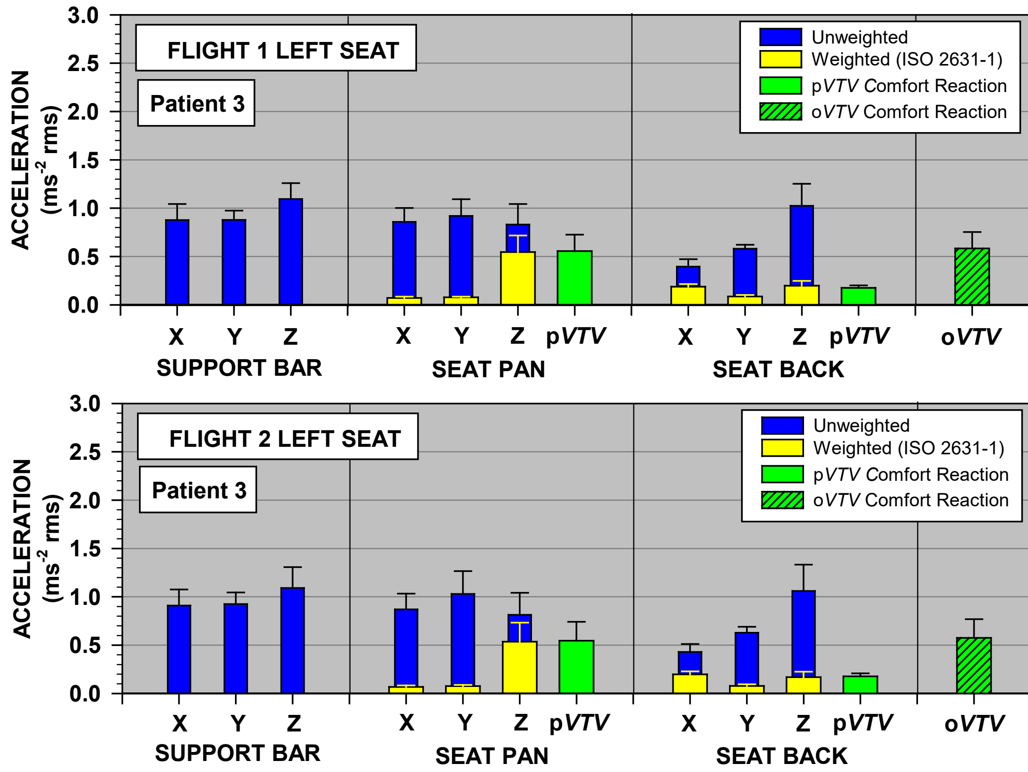

Figure A-12. Mean Unweighted and Weighted Level Flight Overall Accelerations, pVTVs and oVTVs ± One Standard Deviation – Seat

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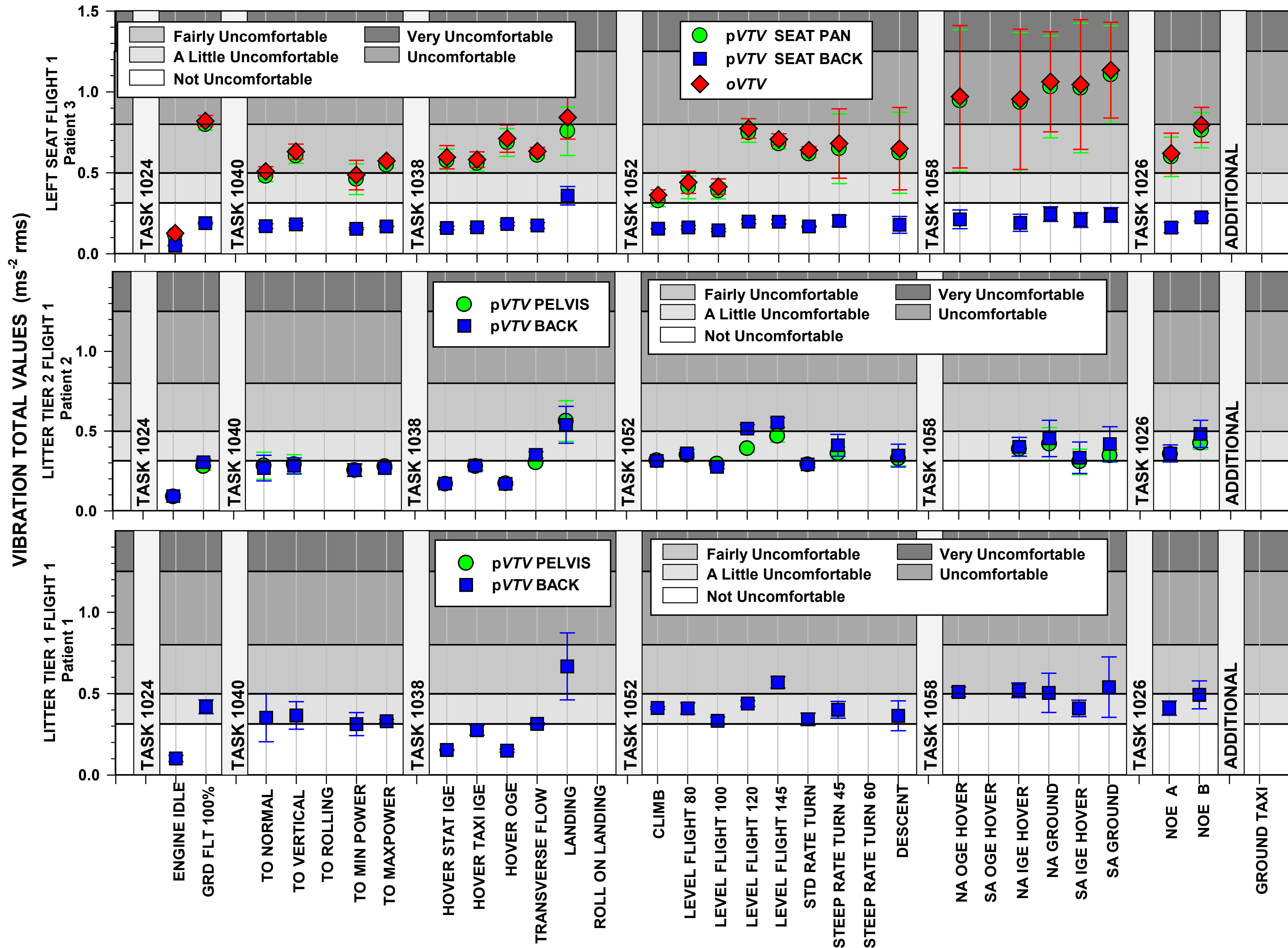

Figure A-13. Mean Vibration Total Values ± One Standard Deviation – Flight 1

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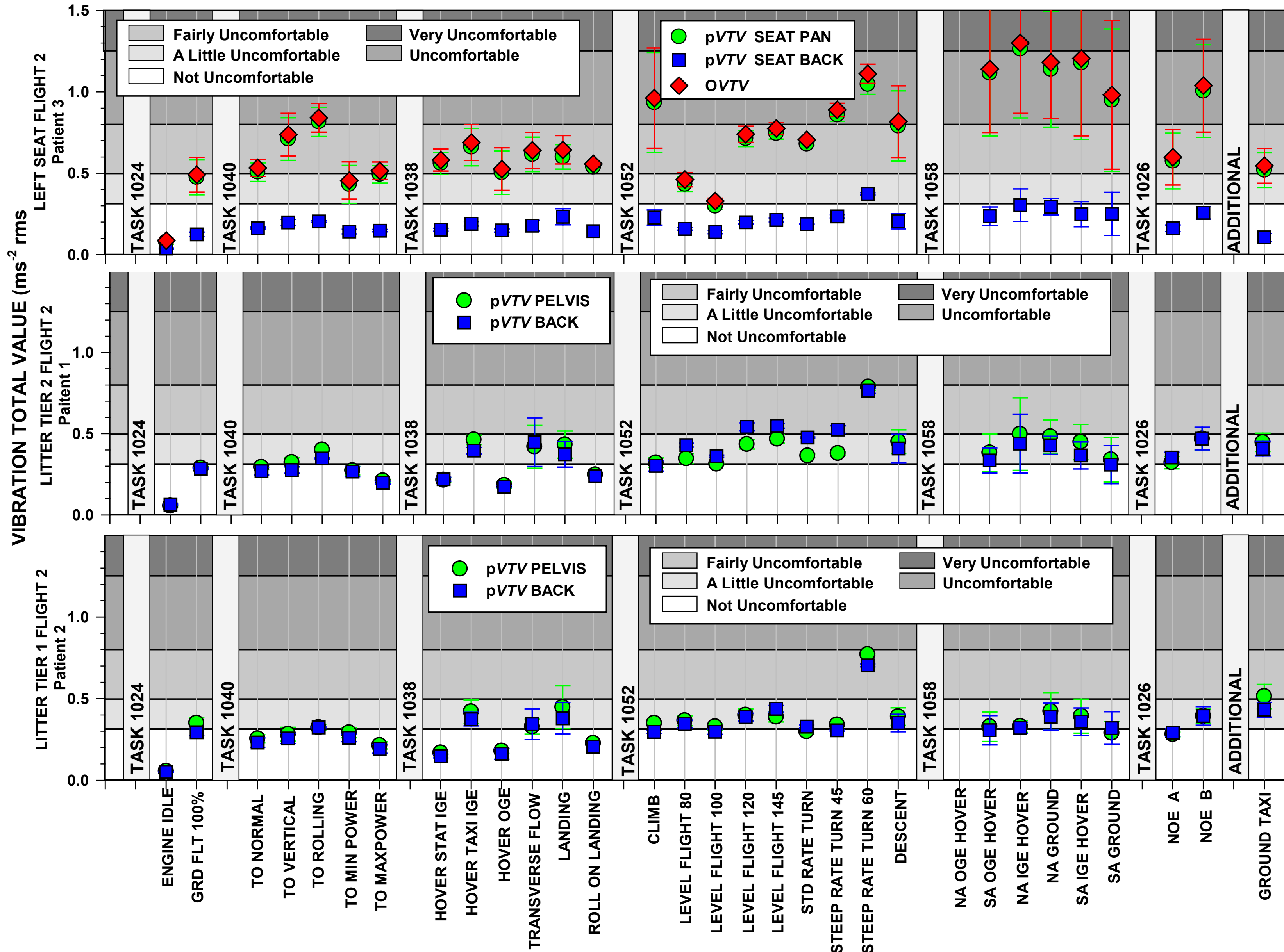

Figure A-14. Mean Vibration Total Values ± One Standard Deviation – Flight 2

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Table A-1. REVER Component Details

Component	Dimensions (L/W/H cm)	Weight (Kg)	Item Identification orNumber
DAU (EME 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 (Powerizer, NiMH, 12V, 4.5Amp-hours)	10.0/7.0/3.5	0.645	TOTAL: 3
Small Batteries (Powerizer, NiMH, 12V, 2.7Amp-hours)	9.0/5.0/3.5	0.395	TOTAL: 3
Accelerometer Packs (Entran or TE Connectivity MEAS EGAX-25/EGAXT-25)	1.9 (diameter) 0.86 (thickness)	0.005 (0.060 w/ cable)	TOTAL: 7
Accelerometer Pads (Ride Quality Meter, RQM, includes embedded triaxial pack)	20.0 (diameter)	0.340 w/ cables	TOTAL: 6
Triggers	7.6 (length) 2.2 (diameter)	0.030 w/cable	TOTAL: 3
Extension Cables	Various lengths	-	

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Table A-2. UH-60L Flight Tasks and Flight Test Conditions Records

Task/Condition	# of Records	
	Flight 1[a,b]	Flight 2
TASK 1024 Before Starting Through Before Leaving Helo Checks		
Engine Idle	3[1]	3
Ground Flight 100%	3	3
TASK 1040 Perform VMC Takeoff		
Takeoff Normal	3	5[6,7]
Takeoff Vertical	3	4
Takeoff Rolling	-	2
Takeoff Minimum Power	4	3
Takeoff Maximum Power	2	2
TASK 1038 Perform Hovering Flight		
Hover Stationary IGE	3	3
Hovering Taxi IGE	3	4
Hover OGE	3	3
Transverse Flow	3[1]	3[5]
Landing	5	3
Roll on Landing	-	1
TASK 1052 Perform VMC Flight Maneuvers		
Climb	3	3[4]
Level Flight 80 KCAS	10[3]	10
Level Flight 100 KCAS	10[1,3]	10[7]
Level Flight 120 KCAS	10[2]	10
Level Flight 145 KCAS	10	10
Standard Rate Turn	3	3
Steep Rate Turn (45 degrees)	6[1]	3
Steep Rate Turn (60 degrees)	-	3
Descent	3	7
TASK 1058 Perform VMC Approach		
Normal Approach to OGE Hover	3	-
Steep Approach to OGE Hover	-	3
Normal Approach to IGE Hover	3	6[4,6]
Normal Approach to Ground	5	4[5]
Steep Approach to IGE Hover	3	6
Steep Approach to Ground	4[1]	5[5]
TASK 2026 Perform Terrain Flight		
Nap-of-the-Earth (NOE) A	5	7[8]
Nap-of-the-Earth (NOE) B	6	5
Additional		
Ground Taxi		6[4,6]

[a]Tier 1 Litter Pelvis VX all channels bad all records; [b]Tier 2 Litter Head LZ all channels bad all records; [1]Tier 2 Litter all channels bad for one record; [2]Tier 2 Litter all channels bad for two records; [3]Tier 2 Litter Pelvis Y bad 6 records; [4]All channels bad 1 record; [5]Tier 1 Pelvis Y bad 1 record; [6]Tier 1 Litter Pelvis Y bad 2 records; [7]Tier 1 Litter Pelvis Y bad 3 records; [8]Tier 1 Pelvis Y bad 6 records; [9]Seat bad 1 record

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Table A-3. UH-60L Overall Unweighted Accelerations: Litter Patient Statistical Results-Effect of Direction (significant difference: P<0.05)

	TIER 1		TIER 2	
	FLIGHT 1	FLIGHT 2	FLIGHT 1	FLIGHT 2
SUPPORT PLATFORM	VX>Y>LZ	VX>Y>LZ	VX>(Y=LZ)	VX>(Y=LZ)
PELVIS	Y>LZ	Y>LZ>VX	LZ>Y>VX	Y>LZ>VX
BACK	Y>LZ>VX	Y>LZ>VX	LZ>Y>VX	Y>LZ>VX
LZ=Longitudinal; Y=Lateral; VX=Vertical				

Table A-4. Overall Unweighted Accelerations: Litter Patient Statistical Results-Effect of Litter Tier (significant difference: P<0.05)

	SUPPORT PLATFORM		PELVIS		BACK	
	Flight 1	Flight 2	Flight 1	Flight 2	Flight 1	Flight 2
DIRECTION						
LZ	T2>T1	T2>T1	T2>T1	T2>T1	T2>T1	T2>T1
Y	T1>T2	T1>T2	T1>T2	T2>T1	T1=T2	T2>T1
VX	T2>T1	T2>T1	-	T2>T1	T1=T2	T2>T1
LZ=Longitudinal; Y=Lateral; VX=Vertical; T1=Tier 1; T2=Tier 2						

Table A-5. UH-60L Overall Unweighted Accelerations: Seat Patient Statistical Results-Effect of Direction (significant difference: P<0.05)

	LEFT SEAT	
LOCATION	FLIGHT 1	FLIGHT 2
SUPPORT BAR	Z>(X=Y)	Z>(X=Y)
SEAT PAN	Y>(X=Z)	Y>X>Z
SEAT BACK	Z>Y>X	Z>Y>X
Note: Seat X = Aircraft Y; Seat Y = Aircraft X		

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