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**VIBRATION MITIGATION ANALYSIS OF
A SEAHAWK HELICOPTER SEAT SUSPENSION
CONCEPT**

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14. ABSTRACT Recent surveys aboard rotary-wing aircraft strongly suggest that aircrew are being exposed to operational vibration associated with the potential for health risk. The objective of this study was to evaluate the effectiveness of a seat suspension concept to mitigate vertical operational vibration and minimize health risk. A Seahawk seat fitted with a magnetorheological active damper system was mounted onto the Six-Degree-of-Freedom Motion Simulator (SIXMODE) located at the Air Force Research Laboratory (AFRL). Nine military volunteers were exposed to multi-axis flight vibration recreated in the SIXMODE. Seat system configurations included LOCKED (no damper), UNLOCKED ON (damper with variable viscosity), and UNLOCKED OFF (damper with constant viscosity). Triaxial accelerations collected at the seat interfaces and subject anatomical sites were used to estimate rms spectra. The ISO 2631-1: 1997 and MIL-STD 1472 were used as guidelines for health risk assessment. The UNLOCKED ON and OFF configurations showed similar results; significant reductions in the vertical acceleration peak associated with the blade passage frequency (~17 Hz) and in the overall vertical acceleration (1-80 Hz) ($P < 0.05$), specifically at the seat/occupant interfaces, as compared to the LOCKED configuration. The weighted seat pan vibration total values (VTV_s) were substantially reduced in the vertical direction and the allowable daily exposures for minimal health risk was increased with the UNLOCKED configurations. Suspension seats can mitigate rotary-wing aircrew health risk. The specific effectiveness of variable viscosity dampers may depend on the vehicle vibration characteristics and the ability to tune the damper with respect to frequency. Additional improvement to aircrew performance may also require consideration of seat interface postural influences.

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PREFACE

This report describes the study conducted by the Air Force Research Laboratory, 711 Human Performance Wing, Airman Systems Directorate (711 HPW/RH) to evaluate the effectiveness of a seat suspension technology developed to mitigate operational vertical vibration transmitted to the Seahawk helicopter pilot while maintaining crashworthiness. The prototype technology is known as the Active Vibration Attenuation Seat Suspension (AVASS) System and its development was sponsored by the Naval Air Systems Command (NAVAIR) located at Patuxent River Naval Air Station. The prototype system was retrofitted to an SH-60S helicopter seat. The 711 HPW/RH owns and operates a human-rated electro-hydraulic multi-axis vibration facility known as the Six Degree-of-Freedom Motion Simulator (SIXMODE). The 711 HPW has also collected operational exposures aboard the HH-60M and other aircraft, and can recreate the associated vibration environments in the facility. This report specifically focuses on evaluating the effectiveness of the AVASS to mitigate the transmission of multi-axis vibration to the occupant compared to the original Seahawk seat. Two seat configurations were evaluated with nine subjects: the LOCKED configuration (to mimic the original seat with no damper) and the UNLOCKED ON configuration (to utilize the active variable viscosity damper system). A third optional configuration was evaluated with seven subject: the UNLOCKED OFF configuration (with constant viscosity damper). Subjects were also asked to complete a vibration and comfort survey after each test session. A secondary objective of the study sought to develop a method for measuring and evaluating muscle electrical activity in the higher frequency operational vibration environment, apply the method to evaluate muscle response before, during, and following vibration exposure, and to explore the possible relationship between vibration and tonic muscle reflex that may lead to fatigue for extended and repeated exposures. Other physiological measurements included heart rate, heart rate variability, breathing rate, and skin temperature. This technical report focuses on the primary objective of the study. The results of the physiological measurements will be presented in a separate technical report. The results of this study can be used to develop appropriate design criteria for vibration mitigation strategies and to identify potential technologies that can be implemented in the near future. These strategies and technologies are essential for effectively reducing the reported symptoms of back pain and injury and for ensuring mission readiness of our aircrew.

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1.0 SUMMARY

The primary purpose of this study was to quantify and evaluate technologies that can mitigate the transmission of operationally-relevant vibration and minimize the discomfort and health risk associated with these exposures. The Active Vibration Attenuation Seat Suspension (AVASS) System was specifically designed to reduce the transmission of vertical vibration to the seated occupant. The primary objective of the study and focus of this report was to evaluate the effectiveness of the AVASS System, installed on a SH-60S helicopter seat, to mitigate multi-axis vibration transmission to human occupants, and to assess changes in the occupational discomfort and health risk associated with seat configuration using the guidelines and criteria provided in current exposure standards.

A Seahawk seat fitted with a magnetorheological damper system was mounted onto the Six-Degree-of-Freedom Motion Simulator (SIXMODE) located at the Air Force Research Laboratory (AFRL 711 HPW/RH). Exposures included 17 Hz vertical vibration at three acceleration levels, a flat spectrum multi-axis signal generated between 1 and 80 Hz, a HH-60M level flight signal collected with the Automatic Vibration Suppression System on (AVSS ON), and a HH-60M level flight signal collected with the AVSS off (AVSS OFF). The latter signal included one hour of exposure with data being collected every five minutes to allow for the evaluation of physiological metrics. Nine subjects participated in the exposures with two seat system configurations including LOCKED (no damper) and UNLOCKED ON (active variable viscosity damper). Seven of the subjects also participated in an optional exposure with the UNLOCKED OFF (constant viscosity damper) configuration. Triaxial accelerations were collected at the seat interfaces and subject anatomical sites including the floor, seat base, seat pan, seat back, leg (knee), chest, and upper spine. These data were processed in constant frequency bands (0.5 Hz) to estimate the rms spectra at each measurement site and for calculating the multi-axis transfer functions between the floor and selected sites. The HH-60M exposure data were also processed in one-third octave proportional frequency bands for assessing discomfort and health risk in accordance with ISO 2631-1: 1997 and MIL-STD 1472.

The UNLOCKED ON and OFF configurations showed similar results; significant reductions ($P < 0.05$) in the prominent vertical acceleration peak associated with the blade passage frequency of the Seahawk (~17 Hz), specifically at the seat/occupant interfaces, as compared to the LOCKED configuration. There were no differences in seat base and seat pan responses to the UNLOCKED ON vs UNLOCKED OFF configurations. It was not clear that the active system was being excited for these exposures. The transfer functions did show shifts in the peak vertical transmission responses occurring around 5 Hz with the LOCKED configuration, to a lower frequency around 2 Hz with the UNLOCKED configurations, with substantial damping of the transmission above 2 Hz. The peak observed around 5 Hz has been associated with human whole-body resonance. The weighted seat pan vibration total values (VTVs) were substantially reduced in the vertical direction with the UNLOCKED configurations; allowable daily exposures for minimal health risk increased from less than two hours to between three and six hours.

Suspension seats can mitigate rotary-wing aircrew health risk. The specific effectiveness of variable viscosity dampers may depend on the vehicle vibration characteristics and the ability to tune the damper with respect to frequency and vibration amplitude. Additional improvement to aircrew performance may also require consideration of seat interface postural influences.

2.0 INTRODUCTION

Epidemiological surveys have consistently reported that ~85% of the rotary-wing aircrew surveyed has suffered back, leg, or neck pain associated with flying helicopters (Hamon, K. et al, 2012). Poor posture, inadequate seats, and aircraft vibration have been targeted as contributing factors but their synergies and physiological mechanisms are unknown. The Business Case Analysis (BCA) conducted by R Cubed Consulting for the Office of the Under Secretary of Defense for Acquisition, Technology and Logistics (OUSD ATL), and Office of the Deputy Under Secretary of Defense Installations and Environment (DUSD T&E) (Hamon, K. et al, 2012) emphasized that musculoskeletal pain and discomfort in these aircrew have a significant negative impact on mission effectiveness and mission readiness with an average yearly avoidable cost of \$239 M. Previous studies have reported that the highest incidence of occupational back pain and back disorders occur in helicopter pilots. Specifically, evidence indicates that aircrew of rotary-wing aircraft may have a greater risk of spinal disease such as disc herniation (Hermes, E. D. et al., 2010).

Low frequency vibration (below 10 Hz) is common in the operation of heavy ground vehicles, including those used in agriculture, excavation, transport (trucks, trains, and buses) and for off-road purposes including military operations. Whole-body resonance in the human body is known to occur between 4 and 8 Hz during seated vertical vibration. In this frequency range, large relative motions occur between the upper and lower torso that are transmitted to the head. It is easy to envision how these relative motions at low frequencies could lead to back discomfort, pain, and even injury from a biomechanics perspective.

Vibration transmission to the upper torso and head decreases at frequencies beyond 10 Hz, unless the exposures are of substantial amplitudes, or the occupant is in contact with a vibrating seat back or head rest. The evaluations that have been conducted during military aircraft operations have shown very low levels of vibration below 10 Hz, even though the rotor speed or propeller rotation frequency (PRF) of rotary-wing/tilt-rotor aircraft typically occurs at low frequencies below 10 Hz. The highest vibration exposures have been primarily observed in the vicinity of the blade passage frequency (BPF), which can be estimated as the number of blades times the PRF. For many 2, 3, and 4-bladed military helicopters/tilt-rotor aircraft, the BPF typically occurs between 10 and 20 Hz, with additional peaks, that can be substantial, observed at multiples of the BPF. The higher frequencies can be felt and are primarily perceived at the interfaces where the body is in contact with the vibrating surface, including the upper legs, buttocks, and back, as indicated in laboratory studies (Smith, S.D., 2008) and in the survey results from the field study conducted on the HH-60M (Smith, S. D. et al., 2014).

There are guidelines that can be applied to assess the discomfort and health risk associated with the occupational vibration exposures (International Organization for Standardization, 1997, ISO-2631-1:1997; Department of Defense, 2012, MIL-STD 1472G). Discomfort and health risk assessments have been conducted on a very limited number of military aircraft platforms. Acceleration data collected during level flight aboard the two-bladed UH-1H Huey (Smith, S.D. & Gerdus, E., 2012) indicated that the pilot would be exposed to the potential for health risk for daily flight durations as low as 3 hours and as high as 10 hours, with the average duration occurring around 5 hours. Acceleration data collected aboard the upgraded AH-1Z SuperCobra (Smith, S. D., 2005) indicated that the vibration was expected to cause varying degrees of

discomfort for the occupants, and expose the aircrew to the potential for health risk in as little as 2 to 3 hours, with the average at approximately 8 hours. Onboard the Air Force CV-22, the exposure levels suggested marginal comfort based on the comfort reactions defined in ISO 2631-1: 1997 (Smith, S. D. et al, 2008). During level flight in airplane mode, where the aircrew are expected to spend most of their flight time, the pilot was exposed to the potential for health risk in as little as 2 to 3 hours, while the flight engineer was exposed to the potential for health risk within 5 to 8 hours. Crew members verbally complained about the seat discomfort. The most recent assessments were conducted aboard the UH-72 Lakota and HH-60M Medevac operated by the Vermont Army National Guard (VT ARNG) (Smith, S. D., et al., 2014). Both aircraft showed that certain flight test conditions were associated with comfort reactions ranging from being considered 'fairly uncomfortable' to even 'very uncomfortable' depending on the station. On the UH-72, the exposure levels indicated that the pilot would be exposed to the potential for health risk within 5.5 and 8.5 hours of level flight at the study's higher airspeed (120 KCAS). The medic would be exposed to the potential for health risk within 3.5 and 6.5 hours of level flight at any of the three level flight airspeeds (80, 100, and 120 KCAS) investigated in the study. On the HH-60M, the exposure levels indicated that the pilot would be exposed to the potential for health risk within 4.8 and 8.3 hours at the higher airspeeds (100 and 120 KCAS); the crew chief station would be exposed to the potential for health risk in as little as 2 hours at the higher airspeed (120 KCAS); and the medic station would be exposed to the potential for health risk between 1 and 5 hours at any of the tested airspeeds. The aircrew subjective survey results for the HH-60M indicated that the highest discomfort/pain and highest vibration perception occurred in those body regions that were in direct contact with the seat or vibrating surface, particularly the buttocks and back. The aircrew did emphasize that posture and the seat were contributing factors to discomfort (US Army Public Health Command, 2014).

The Naval Air Systems Command (NAVAIR) sponsored the development of the Active Vibration Attenuation Seat Suspension (AVASS) System which is designed to specifically reduce the vertical vibration transmitted to helicopter occupants while retaining crash safety performance. Current vibration exposure guidelines and criteria can be applied to evaluate the seating system mitigation properties that may have significant influences on health risk in operational environments. Finally, the system can be used to explore changes in physiological responses that may elucidate the mechanisms by which vibration can contribute to back pain and injury. The results may not only identify technologies that can be implemented in the near future, but also provide knowledge for identifying key contributing mechanisms and the continued improvement of mitigation strategies. These strategies are essential for effectively reducing the reported symptoms of back pain and injury and for ensuring mission readiness of our aircrew.

The primary purpose of this study was to quantify and evaluate technologies that can mitigate the transmission of operationally-relevant vibration and minimize the discomfort and health risk associated with these exposures. The primary objective of this study was to evaluate the effectiveness of the Active Vibration Attenuation Seat Suspension (AVASS) System, installed on a SH-60S helicopter seat, to not only mitigate the transmission of vibration to human occupants in the vertical direction, but also the transmission of vibration in the horizontal directions (multi-axis vibration), and to assess changes in the occupational discomfort and health risk associated with seat configuration using the guidelines and criteria provided in current exposure standards. Subjects were also asked to complete a vibration and comfort survey after each test session. A secondary objective of the study sought to develop a method for measuring

and evaluating muscle electrical activity in the higher frequency operational vibration environment, apply the method to evaluate muscle response before, during, and following vibration exposure, and to explore the possible relationship between vibration and tonic muscle reflex that may lead to fatigue for extended and repeated exposures. Other physiological measurements included heart rate, heart rate variability, breathing rate, and skin temperature. This technical report focuses on the primary objective of the study. The results of the physiological measurements will be presented in a separate technical report.

3.0 METHODS AND PROCEDURES

3.1 Overview

This report focuses on the measurement and analysis of occupant and seat accelerations. A summary of the vibration and discomfort survey ratings is also included. A follow-on report will focus on the EMG and physiological measurements and analysis.

3.2 Facility, Equipment, and Instrumentation

All vibration testing was accomplished in the Six Degree-of-Freedom Motion Simulator (SIXMODE) Human Vibration Facility located in Building 824, Area B, Wright-Patterson AFB, OH. The human-rated SIXMODE is a multi-axis vibration platform capable of recreating operational exposures (Servotest Testing Systems LTD, Egham Surrey, England). The system control operator is in charge of operating the SIXMODE and associated hydraulics from the SIXMODE Operation and Control Station located in the SIXMODE Control Room adjacent to the actual platform. The SH-60S seat with AVASS system was attached to the SIXMODE platform as shown in Figure 1. The SH-60S seat did include a seat pan and seat back cushion, and an adjustable cushion for lumbar support. The AVASS system, when in the unlocked and on configuration, is designed to attenuate vertical vibration transmitted to the occupant. The damper is filled with a magnetorheological (MR) fluid comprised of an oil containing suspended magnetic particles. Application of a magnetic field causes the particles to align along lines of magnetic flux that alter the viscosity of the MR fluid. Varying the magnetic field will vary the fluid viscosity and change its force-transmitting characteristics. The magnetic field can be varied via active feedback of aircraft vibration to change the seat damping characteristics accordingly. Two seat configurations were included in the testing; AVASS system LOCKED (to mimic the response of the original seat with no damper), and AVASS system UNLOCKED ON (to utilize the active variable damper system). A third optional seat configuration was also tested and included the AVASS system UNLOCKED OFF (constant viscosity damper). This configuration limited the damper system to respond without active feedback to change fluid viscosity. The LOCKED configuration used an adjustable bracket clamped onto the damper support tubes at the back of the seat to render the damper ineffective during seat motion.

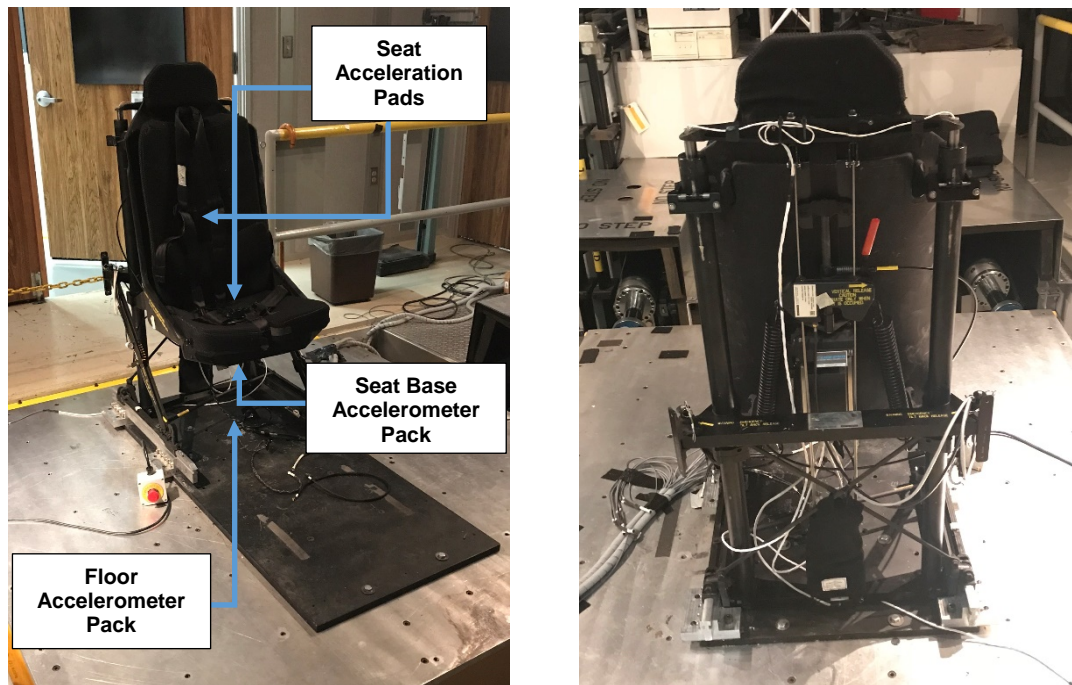


Figure 1. H-60S Seat Mounted onto SIXMODE Platform. Sensor locations also shown.

The platform (floor) beneath the seat was instrumented with a triaxial accelerometer pack. Each triaxial accelerometer pack included three orthogonally-arranged miniature accelerometers (EGAX-25, Entran Devices, Inc., Fairfield, NJ and EGAXT-25, TE Connectivity Measurement Specialties, Hampton, VA) embedded in a Delrin® cylinder. The pack weighed approximately 0.005 kg (~0.06 kg with cable). A triaxial accelerometer pack was also mounted on the rigid seat base beneath the seat pan. Packs were attached with double-sided adhesive tape. Sensor cables were secured using duct tape. Triaxial acceleration pads were placed between the subject and seat pan cushion and seat back cushion. Each triaxial acceleration pad consisted of a flat rubber disk that included an embedded triaxial accelerometer pack at the center. The pad weighed approximately 0.34 kg with cables. The pads measured the accelerations entering the human body at the points of contact with the seating system in accordance with the ISO 2631-1 guidelines. The pads were mounted to the cushion surfaces with double-sided adhesive tape and further secured with duct tape. Figure 2 shows the details of the sensor attachments on the HH-60M during the field study, which was similarly done in the laboratory study. Triaxial accelerometer packs were also attached to the top of the subject knee, onto the chest (manubrium), spine (vicinity of cervical vertebra seven), and top of helmet using double-side adhesive tape and further secured with medical tape. All acceleration data were collected onto a 48 channel data acquisition unit (DAS4800L, EME Corporation, Arnold, MD) located in the SIXMODE Control Room. This unit is part of the SIXMODE Human Data Collection Station that is separate from the SIXMODE Operation and Control Station. Table 1 lists the 24 data channels.

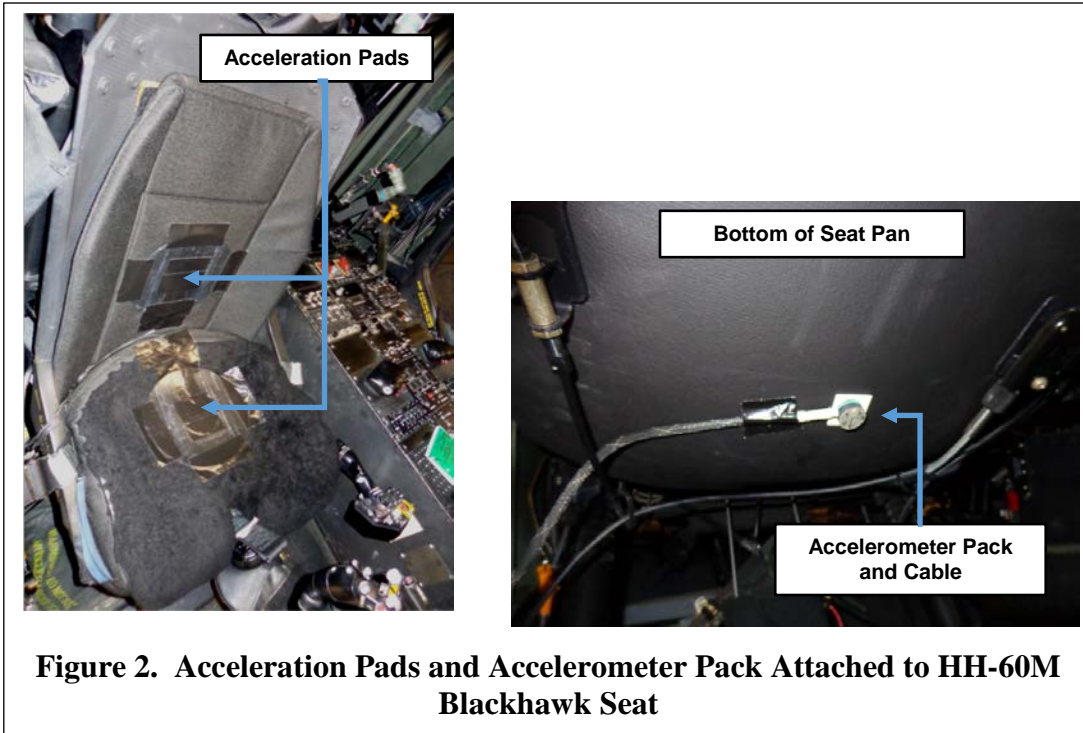


Figure 2. Acceleration Pads and Accelerometer Pack Attached to HH-60M Blackhawk Seat

Table 1. Data Channel Definitions

DATA CHANNELS	MEASUREMENT SITES
1-3	SEAT PAN X, Y, Z
4-6	SEAT BACK X, Y, Z
7-9	FLOOR X, Y, Z
10-12	SEAT BASE X, Y, Z
13-15	LEFT LEG X, Y, Z
16-18	CHEST X, Y, Z
19-21	SPINE (C7) X, Y, Z
22-24	HELMET X, Y, Z

3.3 Vibration Signal Generation

Vibration exposures included single-axis vertical vibration, a multi-axis constant bandwidth flat spectrum signal, and two selected level flight operational signals. The single-axis vibration was generated at 17 Hz at three relative acceleration magnitudes; Low, Medium, and High and ranging from approximately 0.4 to 1.6 ms⁻² rms. The 17 Hz vibration is associated with the blade-passage frequency (BPF) of the HH-60M Blackhawk and is typically where the highest level of vibration occurs for this vehicle and its

variants. The flat spectrum included frequencies between 1 and 80 Hz generated simultaneously in the three orthogonal axes fore-and-aft (X), lateral (Y), and vertical (Z) relative to the seated occupant. All frequency components were at approximately the same acceleration level with an overall level between 1 and 80 Hz of approximately 1.0 ms⁻² rms in each direction, allowing for a more comprehensive evaluation of the seat configuration response characteristics. The two operational signals were selected from field data collected on the HH-60M Medevac owned and operated by the Vermont Army National Guard, Burlington, VT (Smith, S. D. et al., 2014). The first operational signal represented level flight vibration aboard the HH-60M with the AVSS ON. The second operational signal represented level flight vibration aboard the HH-60M with the

AVSS OFF. The effect of this system will be discussed in the Results. All signals were generated from digital time histories using the Iterative Control System (ICS) (Servotest Testing Systems LTD, Egham Surrey, England). Each signal was generated at 1024 samples per second and were 20 seconds in length. The signals were repeated in succession to obtain the desired length of exposure. Figure 3 illustrates sample input acceleration spectra estimated at the floor for the 17 Hz vibration, flat spectrum, and HH-60M signals (see Section 3.6).

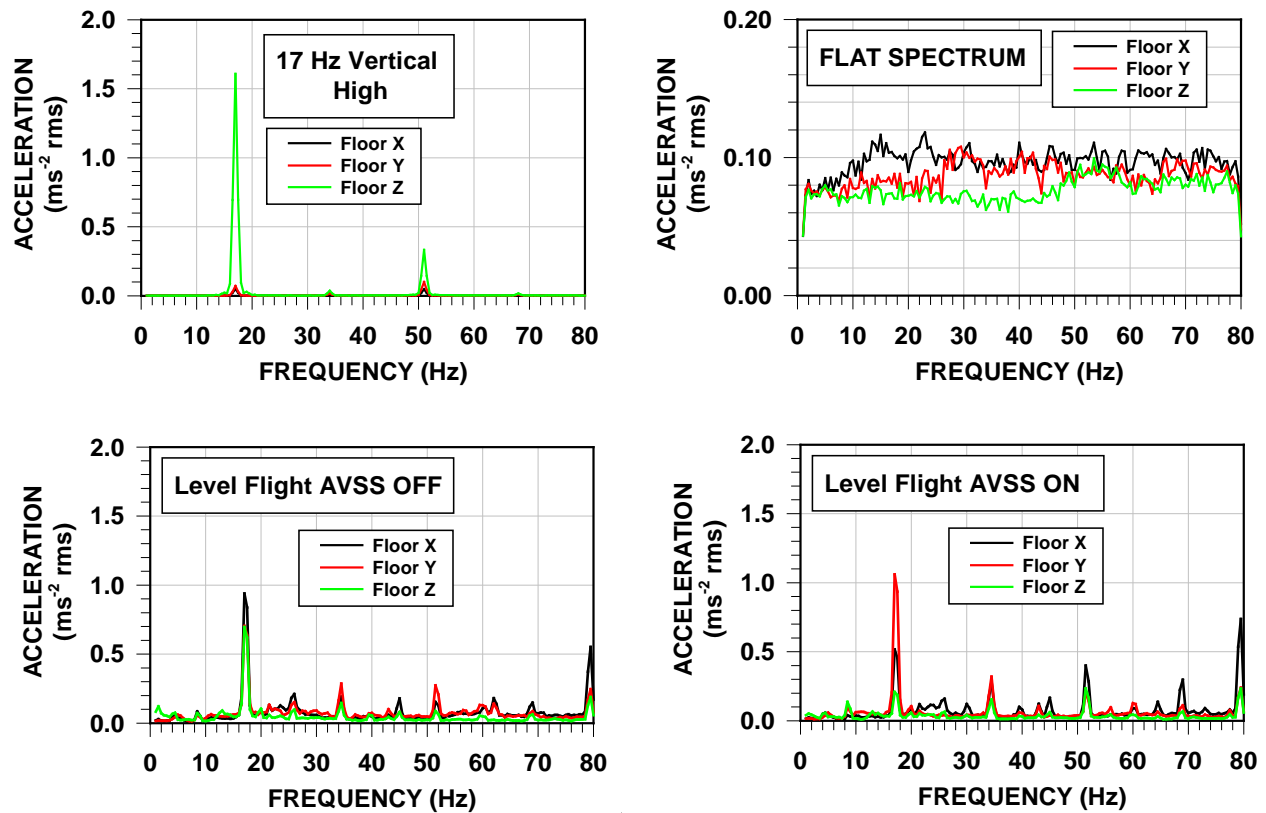


Figure 3. Sample Input Acceleration Spectra

The survey included the assessment of discomfort and pain and vibration perception relative to body regions. The subjects were asked to rate factors such as posture, vibration, seat, and helmet on their contribution to discomfort. A seat questionnaire was also included in the survey and focused on characteristics of the seat pan and seat back.

3.5 Testing Procedures

3.5.1 Subjects.

The human use protocol was approved by the Air Force Research Laboratory Institutional Review Board (AFRL IRB) as well as the AFMSA/SGE-C. Subjects for the study were volunteer active duty members of the US military services. Each subject was required to undergo a hazardous duty evaluation for exposure to acceleration by an approved Medical Consultant. The evaluation included medical screening prior to participation (visual acuity, audiometry, blood

pressure, routine blood work, urinalysis, standard 12-lead EKG, chest x-ray, and complete spine x-rays). Ten subjects, six males and four females, ranging in weight from 60.3 kg to 106.6 kg were approved for testing. One female subject was removed from the study due to a non-related medical incident. Table 2 lists the anthropometric details of the nine final subjects. Subjects wore shorts and top provided by the lab for accommodating sensors, and socks with military boots. The subjects were fitted with a modified HGU-55/P helmet weighing less than 2 kg. The helmet included a wireless headset in the earpiece for audio.

Table 2. Subject Height and Weight

SUB ID	GENDER	HEIGHT (cm)	WEIGHT (kg)		
			LOCKED	UNLOCKED ON	UNLOCKED OFF
1	M	172.7	69.9	72.2	71.2
2	M	172.7	106.6	106.6	105.7
4	F	165.1	76.7	77.8	75.8
5	F	165.1	61.4	61.7	60.3
6	M	170.2	80.1	82.6	-
7	F	170.2	92.2	90.5	88.2
8	M	165.1	62.8	62.4	62.9
9	M	175.3	76.2	77.6	74.4
10	M	182.9	85.3	86.6	-

3.5.2 Training.

Prior to formal testing, all subjects participated in one training session to familiarize them with the equipment and testing sequence. Subjects were instructed on hand signals used to communicate with personnel in the SIXMODE Control Room. For all testing, the subject had access to the emergency stop button that would cause the SIXMODE to immediately stop motion and shut down. The training session included brief exposures to the three vertical acceleration signals at 17 Hz, the multi-axis flat spectrum, and the HH-60M AVSS ON signal. The exposures combined lasted less than 5 minutes. They were then exposed to 15 minutes of the HH-60M AVSS OFF signal.

3.5.3 Formal Test Sessions and Testing Sequence.

All nine subjects participated in two test sessions on separate days to accommodate the AVASS system LOCKED and UNLOCKED ON seat configurations. Five of the nine subjects tested on the LOCKED configuration first; four tested on the UNLOCKED ON configuration first. Seven of the subjects also participated in the optional third test session with the AVASS system UNLOCKED OFF. During vibration exposure, subjects were initially exposed to the three vertical sinusoidal signals at 17 Hz, the flat spectrum, and the HH-60M AVSS ON signal. Acceleration data were collected for 20 seconds for each exposure. The subjects were then exposed to 60 minutes of the HH-60M AVSS OFF signal. Acceleration data were collected for 20 seconds every 5 minutes. Table 3 summarizes the test matrix for each test session. During the entire vibration exposure (lasting approximately 1 hr and 5 min), the subjects were kept occupied by watching an approved video movie.

Table 3. Test Matrix

RUN	EXPOSURE
1	17 Hz Vertical Low Peak
2	17 Hz Vertical Mid Peak
3	17 Hz Vertical High Peak
4	Flat Spectrum
5	HH-60M AVSS ON
6-18	HH-60M AVSS OFF

3.6 Data Collection, Processing, and Analysis

3.6.1 Power or Auto Spectral Density.

For all test runs, data were collected simultaneously for 20 seconds, filtered at 250 Hz, and digitized at 1024 samples per second. A computer program was used to separate the 20-second records for each channel (Table 1) and assemble all channels for a particular record into a table of time histories. For each of the 18 records, the time histories were processed using the MATLAB® Signal Processing Toolbox (The MathWorks, Inc., Natick, MA) to estimate the constant bandwidth spectral content between 1 and 150 Hz for each data channel. 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.

3.6.2 Transfer Function.

The MATLAB® Signal Processing Toolbox (The MathWorks, Inc., Natick, MA) and Welch's Method were also applied to the flat spectrum data to estimate the transfer functions between the floor and seat base, and floor and seat pan. The transfer functions were estimated using a multiple (three)-input/single-output model that takes into account the contribution from the other axes of motion in the calculation of the transfer function and the partial coherences (Bendat, J.S. and Piersol A.G., 1993; Newland D.E., 1984; Naidu P.S., 1996). An example of the system transfer matrix (H) for x, y, and z inputs and the single axis Z output is:

$$\begin{bmatrix} H_{xZ} \\ H_{yZ} \\ H_{zZ} \end{bmatrix} = \begin{bmatrix} S_{xx} & S_{xy} & S_{xz} \\ S_{yx} & S_{yy} & S_{yz} \\ S_{zx} & S_{zy} & S_{zz} \end{bmatrix}^{-1} \begin{bmatrix} S_{xZ} \\ S_{yZ} \\ S_{zZ} \end{bmatrix} \quad (1)$$

where S_{xx} , S_{yy} , and S_{zz} are the auto-spectra of the respective inputs, S_{xy} , S_{xz} , S_{yx} , S_{yz} , S_{zx} , and S_{zy} are the cross-spectra between the respective inputs, and S_{xZ} , S_{yZ} , and S_{zZ} are the cross-spectra between the respective inputs and the single output in the Z direction. Similar equations can be written for outputs X and Y. Further details regarding the multiple-input/single-output transfer functions can be found in Smith, S.D & Mosher, S.E., 2006; Smith, S.D., et al., 2007.

3.6.3 Overall Unweighted and Weighted Acceleration Levels.

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 the peak accelerations and to identify directional characteristics.

Each 20-second 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. These data were used to assess the exposures (helicopter signals only) in accordance with the current standards.

The overall unweighted acceleration level, a_{uw} , between 1 and 80 Hz, was calculated at each measurement site using the root-mean-square (rms) acceleration, a_{rms} , associated with each one-third octave frequency band:

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

where a_{rmsi} is the rms acceleration associated with the i th frequency component.

3.6.4 Discomfort and Health Risk Assessments.

The assessments of discomfort (comfort reaction) and health risk followed the guidelines provided in ISO 2631-1 and MIL-STD 1472G. The frequency weightings and multiplying factors listed in Table 4, based on human sensitivity to the location, frequency, and direction of vibration, were used for the assessments. Figure 4 illustrates the frequency weightings W_d , W_k , and W_c .

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 of the seated occupant using the one-third octave rms accelerations:

$$a_w = \left[\sum_i W_{ij}^2 a_{rmsi}^2 \right]^{\frac{1}{2}} \quad (3)$$

where j represents the particular frequency weighting (d , k , or c) depending on the location and direction (Table 4), i represents the i th frequency component, and a_{rmsi} is the one-third octave acceleration level at center frequency i . For assessing comfort reaction, the point vibration total value ($pVTV$) was calculated at both the seat pan and seat back as the vector sum of the weighted fore-and-aft, lateral, and vertical accelerations after applying the appropriate multiplying factors for the measurement location (seat pan or seat back):

$$pVTV = \left[k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2 \right]^{\frac{1}{2}} \quad (4)$$

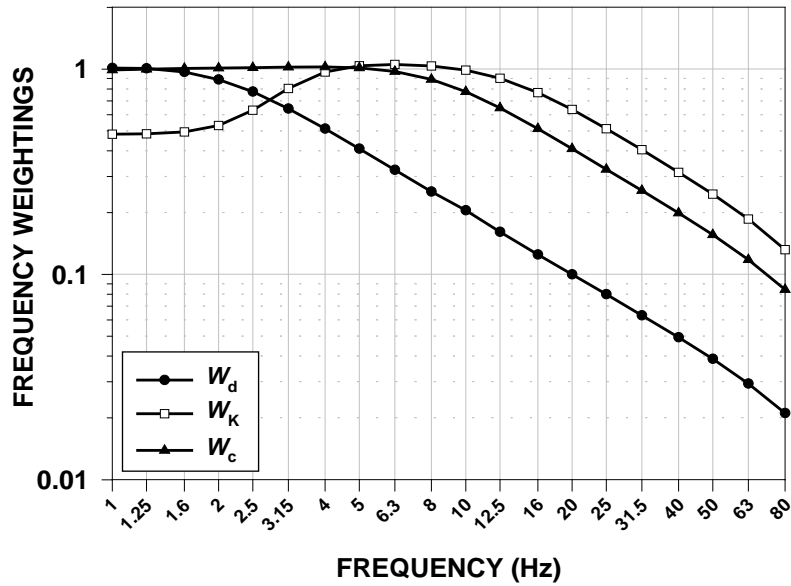


Figure 4. ISO 2631 Frequency Weightings W_d , W_k , and W_c (ISO 2631-1: 1997)

Table 4. ISO 2631 Frequency Weightings and Multiplying Factors (ISO 2631-1: 1997)

Direction	HEALTH RISK		COMFORT REACTION			
	Seat Pan		Seat Pan		Seat Back	
	Frequency Weighting	Multiply Factor	Frequency Weighting	Multiply Factor	Frequency Weighting	Multiply Factor
X	W_d	$k = 1.4$	W_d	$k = 1.0$	W_c	$k = 0.8$
Y	W_d	$k = 1.4$	W_d	$k = 1.0$	W_d	$k = 0.5$
Z	W_k	$k = 1.0$	W_k	$k = 1.0$	W_d	$k = 0.4$

The overall vibration total value ($oVTV$) was calculated as the vector sum of the seat pan and seat back $pVTVs$. The $oVTVs$ 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”.

For assessing health risk, the highest weighted seat pan acceleration in any axis (fore-and-aft, lateral, or vertical) was used after applying the appropriate multiplying factors given in Table 4. The ISO 2631-1: 1997 also states that the vector sum of the weighted accelerations at the seat pan ($pVTV$) can be used when vibration in two or more axes are similar after applying the appropriate multiplying factors for health risk (Table 4). The weighted data were compared to the ISO Health Guidance Caution Zones (ISO 2631-1: 1997, Annex B, Figure B.1). For weighted accelerations falling below the lower boundary of the ISO Health Guidance Caution Zones for the expected

duration, health risks are unlikely. For those levels falling between the two boundaries, caution is given with respect to health risk, or there is a potential for health risk. For those levels falling above the upper boundary, health risks are likely for repeated occupational exposures.

4.0 RESULTS

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

4.1 Acceleration Frequency Response Characteristics

4.1.1 Flat Spectrum Frequency Response.

Figure A-1 illustrates sample acceleration spectra estimated at the seat base for the LOCKED, UNLOCKED ON, and UNLOCKED OFF seat configurations. The figure shows a strong similarity between the multi-axis responses with the UNLOCKED ON and UNLOCKED OFF configurations. For all three seating configurations, the higher frequency vibration, particularly notable in the fore-and-aft (X) direction, is most likely due to seat resonances that may be influenced by any seat adjustment mechanism or even the addition of the suspension components and associated mounting at the seat back. Even when in the LOCKED configuration, these components are still present (see Figure 1). The most notable difference between the LOCKED configuration vs both UNLOCKED configurations relative to the human occupant occurred in the vertical (Z) direction. Both UNLOCKED configurations show a peak around 2 – 3 Hz followed by damping of the vibration at the higher frequencies as compared to the LOCKED configuration.

Figure A-2 illustrates the mean magnitude of the seat transfer function between the input at the floor and respective outputs at the seat base and seat pan. The output/input relationships are only shown for the same direction and not for cross-axis influences. All subjects showed similar responses; although the magnitudes of the peak responses varied among the subjects, the frequency location of the peak responses were consistent. The mean transfer functions were fairly identical between the UNLOCKED ON and UNLOCKED OFF configurations. The plots do show the effect of the seat configuration on the frequency location and peak magnitude as observed in Figure A-1 in the vertical direction. For the LOCKED configuration, a small peak was observed between 4 and 5 Hz for all subjects; the peak being magnified slightly at the seat pan. This peak was associated with human whole-body resonance. The suspension system (both ON and OFF) effectively shifted the peak to a lower frequency around 2-3 Hz, dampened the vibration in the vicinity of whole-body resonance (4-5 Hz), as well as higher frequencies associated with helicopter operation, particularly at the BPF (17 Hz).

4.1.2 HH-60M Level Flight Acceleration Spectra.

Figure A-3 illustrates the acceleration spectra estimated at the seat base, seat pan, seat back, and helmet for one subject exposed to the HH-60M AVSS ON signal. Figure A-4 illustrates the acceleration spectra estimated at the seat base, seat pan, seat back, and helmet for one subject exposed to the HH-60M AVSS OFF signal. As expected, a prominent acceleration peak was observed around 17 Hz for both exposures regardless of direction which has been associated with the blade passage frequency (BPF) of the Blackhawk helicopter. The figures show that dampening of the 17 Hz peak occurred in the vertical (Z) direction with the AVSS ON as compared to the AVSS OFF. In contrast, amplification of the 17 Hz peak occurred in the lateral

(Y) direction with the AVSS ON as compared to the AVSS OFF. In addition, prominent peaks were also observed at multiples of the BPF. These peaks could be higher than the BPF peak, particularly with the AVSS ON and depending on the direction (note Base Z and Back Z in Figure A-3). It is noted that other environmental factors may have affected this behavior.

4.2 Unweighted Peak and Overall Accelerations

4.2.1 Peak Acceleration Comparison.

Figure A-5 illustrates the mean 17 Hz peak acceleration magnitudes \pm one standard deviation among the subjects at the seat base, seat pan, seat back, chest, and helmet for the three seat configurations with the 17 Hz vertical sinusoidal exposures. It was noted that the 17 Hz vertical (Z) input acceleration did result in the generation of horizontal (X, Y) vibration depending on the measurement site. The figure also illustrates the mean 17 Hz acceleration peaks \pm one standard deviation extracted from the two HH-60M signals (AVSS ON and AVSS OFF) among the subjects at the seat base, seat pan, seat back, chest, and helmet for the three seat configurations. For the HH-60M AVSS OFF exposure, the acceleration spectra associated with the 20-s record collected at the beginning of the 1-hour exposure was used to identify the peak magnitude and frequency location. Repeated Measures (RM) Analysis of Variance (ANOVA) and the Tukey Pairwise Comparison were used to statistically evaluate the effect of seating configuration on the three levels of 17 Hz vertical (Z) peaks and the 17 Hz peaks extracted from the two HH-60M signals (AVSS ON and AVSS OFF). Those measurement sites and directions showing significant reductions with both UNLOCKED configurations are marked with a red asterisk. Those measurement sites and directions showing a significant increase with both UNLOCKED configurations are marked with a black asterisk. For the 17 Hz exposures, significant differences are only shown for the vertical (Z) axis.

For the 17 Hz exposures, the measurement sites depicted in Figure A-5 showed a tendency for lower Z acceleration levels with both UNLOCKED configurations as compared to the LOCKED configuration. These observations were statistically significant ($P < 0.05$) for the seat base, seat pan, and seat back for all three acceleration levels. Both UNLOCKED configurations showed significantly lower Z accelerations as compared to the LOCKED configuration at the helmet for the MED and HIGH magnitudes. No differences were observed in the Z peaks among the seat configurations at the chest. There were no significant differences in the Z peaks found between the UNLOCKED configurations at any of the illustrated measurement sites.

With the HH-60M AVSS ON exposure, both UNLOCKED configurations showed significantly lower 17 Hz Z peaks as compared to the LOCKED configuration at the seat base and seat pan (red asterisk), but both showed a significantly higher 17 Hz Z peak at the seat back (black asterisk) ($P < 0.5$). The AVSS ON exposure for both UNLOCKED configurations resulted in significantly lower lateral (Y) peaks at the seat base, seat pan, and seat back (red asterisk). The UNLOCKED configurations showed a significantly lower fore-and-aft (X) peak at the seat base (red asterisk), but significantly higher fore-and-aft (X) peaks at the seat pan and seat back (black asterisk). No significant differences were observed among the seat configurations for the AVSS ON exposure at the chest and helmet in any direction. No significant differences were observed between the UNLOCKED configurations for any of the illustrated measurement sites in any direction.

With the HH-60M AVSS OFF exposure, both UNLOCKED configurations resulted in significantly lower 17 Hz Z peaks at the seat base, seat pan, seat back, and helmet (red asterisk), with no differences observed at the chest. The AVSS OFF exposure for both UNLOCKED configurations showed statistically lower Y peaks at the seat base, seat pan and seat back (red asterisk) ($P < 0.5$) with no differences observed at the chest and helmet. The UNLOCKED configurations showed a significantly lower X peak at the seat base (red asterisk), but significantly higher X peaks at the seat pan and seat back (black asterisk), similar to the observations with the AVSS ON. The AVSS OFF with the UNLOCKED configurations showed no differences in the X peak at the chest, and mixed results at the helmet. No significant differences were observed between the UNLOCKED configurations for the illustrated measurement sites in any direction except at the helmet where mixed results were observed.

4.2.2 Unweighted Overall Acceleration (1-80 Hz).

Figures A-6 and A-7 illustrate the mean unweighted overall accelerations \pm one standard deviation among the subjects for the HH-60M AVSS ON and HH-60M AVSS OFF exposures, respectively, at the seat base, seat pan, seat back, chest, leg, spine, and helmet for the three seat configurations. It is noted that the mean value calculated among the subjects for the AVSS OFF exposure was estimated from the mean value of the 13 records collected over the one-hour exposure for each subject. Analysis of the overall accelerations over the one-hour period indicated that very small changes, if any, occurred in the values for any given subject and measurement site. RM ANOVA and the Tukey Pairwise Comparison were used to statistically evaluate the effect of seat configuration on the unweighted overall accelerations.

Figures A-6 and A-7 show that the UNLOCKED seat configurations produced dampened overall accelerations at the seat base, seat pan, and seat back in most directions, with mixed or similar results among the configurations at the other sites. For both the AVSS ON and AVSS OFF exposures, the UNLOCKED configurations showed significant reductions in the overall lateral (Y) and vertical (Z) vibration at the seat base, seat pan and seat back ($p < 0.05$) (red asterisk). No significant differences were observed in the fore-and-aft (X) direction with the AVSS ON at these three measurement sites. The reduction in the overall X acceleration was significant with the AVSS OFF exposure at the seat base and seat pan (red asterisk), but not for the seat back. The AVSS ON exposure showed no significant effects in the X and Y accelerations and mixed results for the Z acceleration at the chest and helmet. The AVSS OFF exposure showed a significant reduction in the overall Z acceleration at the helmet for both UNLOCKED configurations (red asterisk), with no significant effects observed at the chest in any direction. The only significant reduction observed at the spine occurred in the X direction (red asterisk) with the AVSS ON and the UNLOCKED configurations. No significant effects were observed at the leg for either exposure in any direction. No significant differences were observed for either exposure between the UNLOCKED configurations in any direction, except where mixed results were found.

4.3 Discomfort and Health Risk Assessments (ISO 2631-1)

4.3.1 Comfort Reaction Comparison.

Figures A-8 and A-9 illustrate, with the AVSS ON and AVSS OFF exposures, respectively, the mean weighted overall accelerations \pm one standard deviation in each direction at the seat pan and seat back, the $pVTV$ at the seat pan and seat back for assessing comfort reaction, and the combined σVTV for assessing comfort reaction for the two measurement sites. The figures show

that the highest weighted overall vibration occurred in the vertical (Z) direction at the seat pan, particularly with the LOCKED configuration. RM ANOVA and the Tukey Pairwise Comparison were used to statistically evaluate the effect of seat configuration on the weighted overall accelerations used to assess comfort reaction (ISO 2631-1). With both the AVSS ON and AVSS OFF exposures, the most significant effects were seen at the seat pan in the weighted overall Z acceleration, the seat pan *pVTV*, and the *oVTV*. Both UNLOCKED configurations were similar and showed significant reductions in the weighted values as compared to the LOCKED configuration ($p < 0.05$) (red asterisk). With the AVSS ON, this reduced the expected comfort reaction from “Fairly Uncomfortable” to “A Little Uncomfortable”, except for the *oVTV*. With the AVSS OFF, this reduced the expected comfort reaction from “Uncomfortable” to “Fairly/A Little Uncomfortable”. The similarities in the weighted accelerations at the seat back may have had some small effect on the comfort reactions associated with the weighted overall acceleration levels.

4.3.2 Health Risk Comparison.

Figures A-10 and A-12 illustrate, with the AVSS ON and AVSS OFF exposures, respectively, the mean weighted overall accelerations \pm one standard deviation in each direction and for the seat pan *pVTV* for assessing health risk. The figures show, as with the weighted values for assessing comfort reaction, that the highest weighted overall accelerations occurred in the vertical (Z) direction, particularly with the LOCKED configuration. RM ANOVA and the Tukey Pairwise Comparison were used to statistically evaluate the effect of seat configuration on the weighted overall accelerations used to assess health risk (ISO 2631-1). For both the AVSS ON and AVSS OFF exposures, the UNLOCKED configurations were similar and showed significant reductions in the weighted overall vertical (Z) acceleration and seat pan *pVTV* for assessing health risk ($p < 0.05$) (red asterisk). Figures A-11 and A-13 depict the minimum daily exposure durations associated with the potential for health risk based on both the seat pan Z overall accelerations and the seat pan *pVTV* for each subject for the AVSS ON and AVSS OFF exposures, respectively. There are no health risks associated with exposure durations below these minimum values. The figures show that the use of the *pVTV* results in more conservative (lower) minimum exposures, particularly with the AVSS ON exposure, where notable X and Y accelerations occurred relative to the Z acceleration (see Figure A-10). However, as with the comfort reactions, the relatively differences between the LOCKED configuration and the UNLOCKED configurations were greater with the AVSS OFF, where relatively high vertical vibration occurred. For the AVSS ON exposure, the daily minimum exposure duration for potential health risk was increased from approximately 4 – 7 hours with the LOCKED configuration, to greater than 8 hours with the UNLOCKED configurations using the weighted seat pan Z acceleration; and increased from approximately 3 – 4 hours with the LOCKED configuration, to 4 – 7 hours with the UNLOCKED configurations using the seat pan *pVTV*. For the AVSS OFF exposure, the daily minimum exposure duration for potential health risk was increased from approximately 1 - 2 hours with the LOCKED configuration, to around 4 hours and greater with the UNLOCKED configurations using the weighted seat pan Z acceleration; and increased from less than 1 – 2 hours with the LOCKED configuration, to around 3 hours and greater with the UNLOCKED configurations using the seat pan *pVTV*. Higher potential health risk exposure durations beyond 6 hours were associated with using the seat pan Z acceleration for the assessment as compared to using the seat pan *pVTV*, which included contributions from the horizontal accelerations.

4.3.3 Vibration and Discomfort Survey.

Figure A-14 illustrates the mean discomfort/pain ratings and Figure A-15 illustrates the mean vibration perception ratings among the subjects for the three seat configurations. Large variations were observed among the subjects. There tended to be higher ratings for vibration perception (substantial vibration) as compared to discomfort and pain. The One Way Repeated Measures ANOVA on Ranks were applied to the ratings. No significant differences were found among the seating configurations. Figure A-14 suggests that more discomfort/pain occurred in the lower back and possibly the buttocks. This was only significant when comparing the lower back to the chest and upper leg ratings ($p < 0.05$). Figure A-15 suggests that the subjects perceived more vibration at the feet and face. This was only significant when comparing the feet ratings to those of the chest, upper leg, and upper back, and when comparing the face ratings to those of the chest ratings ($p < 0.05$). In addition, the buttocks ratings were significantly higher as compared to the chest ratings for vibration perception ($p < 0.05$).

Figure A-16 illustrates the mean ratings for discomfort contributing factors. The figure suggests that posture and the helmet contributed the most to discomfort, while temperature contributed very little. Posture, vibration, seat, and helmet contributed significantly higher than temperature to discomfort ($p < 0.05$). No other differences were significant.

Figure A-17 illustrates the mean seat ratings. Seat pan cushion contour, thigh support, and cushion were generally rated as ok, although more variation in the ratings occurred with cushioning with some subjects rating as too thin (rating 3), while others rated as too hard (rating 5). Seat back cushion contour was generally rated as ok. Seat back lumbar support ratings tended more towards being ok as compared to not enough. There was an adjustable lumbar support pad provided with the seating system that was used during the tests. As with the seat pan cushioning ratings, the seat back cushioning was generally rated as ok, with some subjects rating as too thin (rating 3), while others rated as too hard (rating 5).

5.0 DISCUSSION AND CONCLUSIONS

This study sought to evaluate the effectiveness of a seat suspension concept to mitigate vertical operational vibration and minimize health risk. Specifically, the study focused on evaluating a magnetorheological active damper system (AVASS) configured in a Seahawk helicopter pilot seat. Seat system configurations included LOCKED (no damper), UNLOCKED ON (active damper with variable viscosity), and UNLOCKED OFF (damper with constant viscosity). Triaxial accelerations collected at the seat interfaces and subject anatomical sites were used to estimate rms spectra. The ISO 2631-1: 1997 and MIL-STD 1472 were used as guidelines for health risk assessment.

The UNLOCKED ON and OFF configurations showed similar results; significant reductions in the vertical acceleration peak associated with the blade passage frequency (~17 Hz) and in the overall vertical acceleration (1-80 Hz) ($P < 0.05$), specifically at the seat/occupant interfaces, as compared to the LOCKED configuration. The weighted seat pan vibration total values (VTV_s) were substantially reduced in the vertical direction and the allowable daily exposures for minimal health risk was increased with the UNLOCKED configurations.

The exposure to the flat spectrum signal allowed for a more detailed assessment of the suspension system effects over the frequency range of 1 to 80 Hz. The multi-axis transfer functions calculated between the input accelerations at the platform floor and the seat base and seat pan, did show the expected coupling of the occupant and seat with the LOCKED configuration; the generation of a transmissibility peak around 4 - 5 Hz, particularly at the seat pan, in the vicinity of whole-body resonance in the vertical direction. As typical of vehicle suspension systems, the peak shifted to a lower frequency around 2 – 3 Hz with both UNLOCKED configurations, and showed substantial mitigation of higher frequency vibration, including vibration in the vicinity of 17 Hz associated with the Seahawk (also Blackhawk variants) BPF.

Given the similarity between the results for the UNLOCKED ON (variable viscosity damper) and UNLOCKED OFF (constant viscosity damper), it was not clear whether the input accelerations were high enough to effectively active the variable viscosity damper system (AVASS) as designed. It is speculated that the acceleration levels used to initially tune the system were higher than that measured at the occupant/seat interface in the HH-60M field study, with and without the active vibration suppression system (AVSS ON and AVSS OFF, respectively). Recent field data collected on the UH-60L, which did not include the AVSS, did show seat pan *pVTVs* that were higher than the seat pan *pVTV* estimated for the HH-60M AVSS ON (Smith, S.D. & Chervak, S.G. (2018), but were similar to the seat pan *pVTV* estimated with the HH-60M AVSS OFF.

Suspension seats can mitigate rotary-wing aircrew health risk. The specific effectiveness of variable viscosity dampers will depend on the vehicle vibration characteristics, specifically with regard to the multi-axis vibration being transmitted to the occupant, and the ability to tune the damper with respect to the dominant magnitudes, directions, and frequencies. Unfortunately, there are currently no formalized criteria based on human data to aid in the design of these systems. It is anticipated that such criteria will be developed in the near future, as the limited database on occupant-related vibration aboard military aircraft is expanded. It is important that, when developing these systems, the multi-axis characteristics of the vibration transmitted to the occupant is understood, since relatively high levels of vibration can be transmitted to the occupant in all three axes, fore-and-aft (X), lateral (Y), and vertical (Z). Additional improvement to aircrew performance may also require consideration of occupant anthropometry and seat/occupant interface postural influences.

6.0 REFERENCES

- Bendat, J.S. and Piersol A.G., **Engineering Applications of Correlation and Spectral Analysis**, New York, J. Wiley, 1993.
- 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.
- Hamon, K., Healing, R., Contarino, R., Ellenbecker, D., *Business Case Analysis: Improve Combat Readiness and Mission Effectiveness by Eliminating Avoidable Helicopter Seating Related Injuries*, R Cubed Consulting, Final Report, OUSD (AT&L), DUSD (I&E), 2012.
- Hermes, E.D., Webb, T.S., and Wells, T.S., “Aircraft Type and Other Risk Factors for Spinal Disorders: Data from 19,673 Military Cockpit Aircrew”, *Aviation, Space, and Environmental Medicine*, **81**, 9, Sep, 2010.
- International Standards Organization (ISO). (1997). *Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration – Part 1: General Requirements*. ISO 2631-1:1997.
- Naidu P.S., **Modern Spectrum Analysis of Time Series**. CRC Press, Boca Raton, 1996.
- Newland D.E., **An Introduction to Random Vibrations and Spectral Analysis**, 2nd ed., New York, Longman Inc., 1984.
- Pope, M.H., Donnermeyer, D., Wilder, D.G., et al., *The Effects of Helicopter Vibration on the Spinal System*. In: University of Vermont Annual Progress Report, Contract No. DAMD 17-82-C-2153, US Army Medical Research and Development Command, Fort Detrick, MD, Sep 1983
- Smith, S.D., Super Cobra (AH-1Z) Human Vibration Evaluation. AFRL-HE-WP-TR-2005-0114, Air Force Research Laboratory, Wright-Patterson AFB OH, Aug 2005.
- Smith, S.D., “Dynamic Characteristics and Human Perception of Vibration Aboard a Military Propeller Aircraft”, *International Journal of Industrial Ergonomics*, **38**, 2008, pp 868-879.
- Smith, S.D. and Chervak, S.G., “Aircrew Multi-Axis Vibration Exposure Aboard the UH-60L Blackhawk Helicopter”, Presentation and *Proceedings of the 56th Annual SAFE Symposium*, Grand Sierra Resort and Casino, Reno, NV, 15-17 Oct 2018.
- Smith, S.D., Chervak, S., Steinhauer, B., *Vibration Characterization and Health Risk Assessment of the Vermont Army National Guard UH-72 Lakota and HH-60M Medevac*, AFRL-RH-WP-TR-2014-0053, Wright-Patterson AFB OH, April, 2014.

- Smith, S.D., Gerdus, E., “Characterization and Assessment of Pilot Vibration Exposure Aboard the UH-1H Huey Helicopter”, *Proceedings of the 4th American Conference on Human Vibration*, Hartford Connecticut, 13-15 Jun 2012.
- Smith, S.D., Jurcsisn, J.G., Bowden, D.R., CV-22 Human Vibration Evaluation, AFRL-RH-WP-TR-2008-0095, Air Force Research Laboratory, Human Effectiveness Directorate, Wright-Patterson AFB OH, 2008.
- Smith, S.D and Mosher, S.E., “Vibration Transmission Characteristics of the Upper Torso During Exposure to Single- and Combined-Axis Vibration”, *Proceedings of the 41st United Kingdom Group Meeting on Human Responses to Vibration*, QinetiQ, Farnborough, Hampshire, England, 20-22 Sep 2006.
- Smith, S.D., Mosher, S.E., Bowden, D.R., Walker, A.Y., Jurcsisn, J.G., “Head Transmissibility Characteristics During Single- and Combined-Axis Vibration Exposures”, *Proceedings of the 42nd United Kingdom Conference on Human Responses to Vibration*, Institute of Sound and Vibration Research, University of Southampton, Southampton, England, 10-12 Sep 2007.
- U.S. Army Public Health Command, Postural Assessment of Aircrew During Flight Operations Aboard Helicopters of the Vermont Army National Guard, Ergonomics Program Report No. S.001641, Nov 2014.
- Welch, P.D. (1967), “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.

APPENDIX A

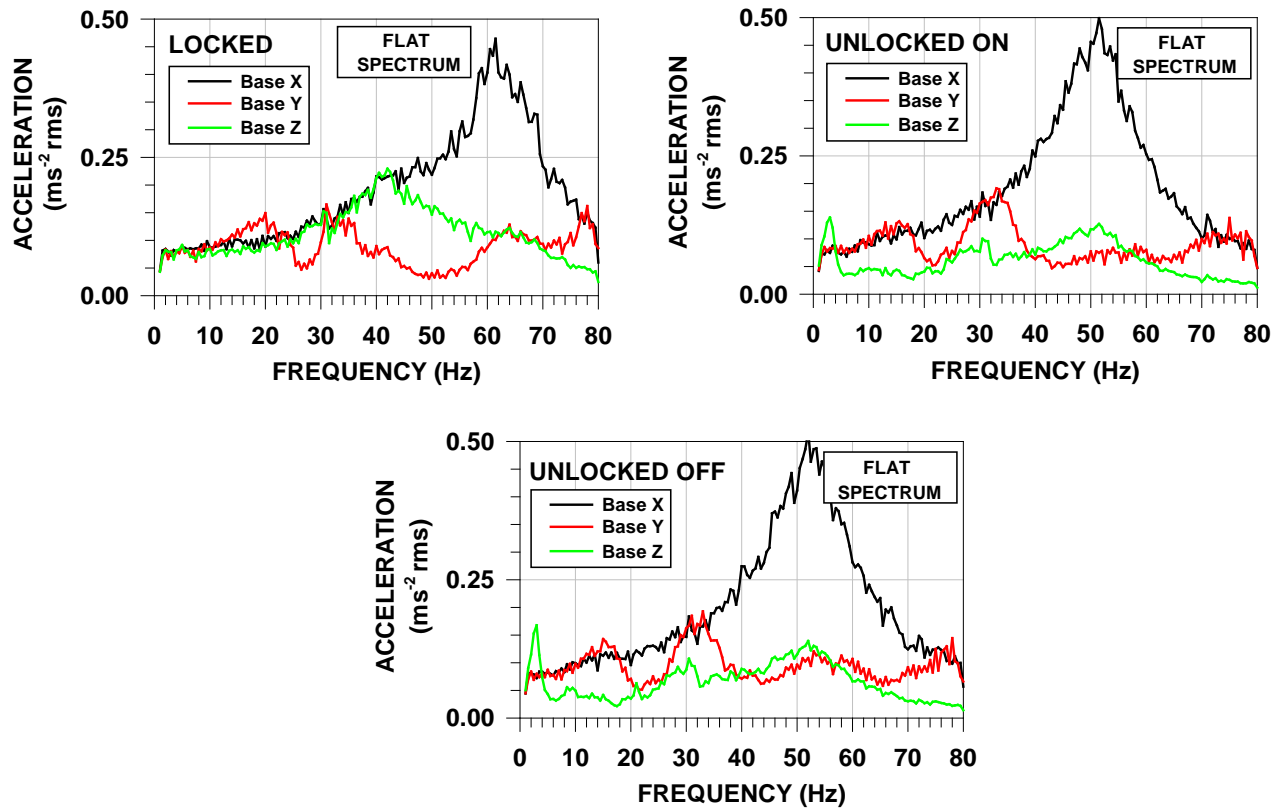
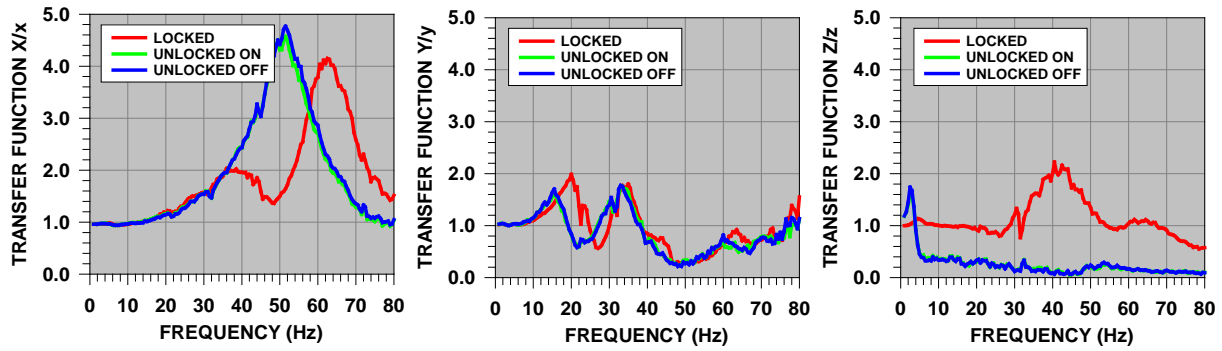


Figure A- 1. Sample Flat Spectrum Acceleration Spectra (Subject 9)

Seat Base Transfer Functions



Seat Pan Transfer Functions

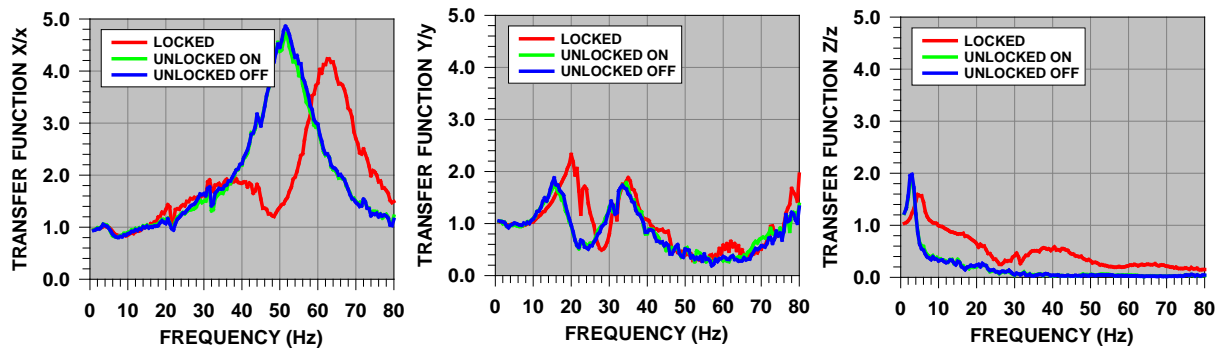


Figure A- 2. Mean Transfer Function Magnitudes

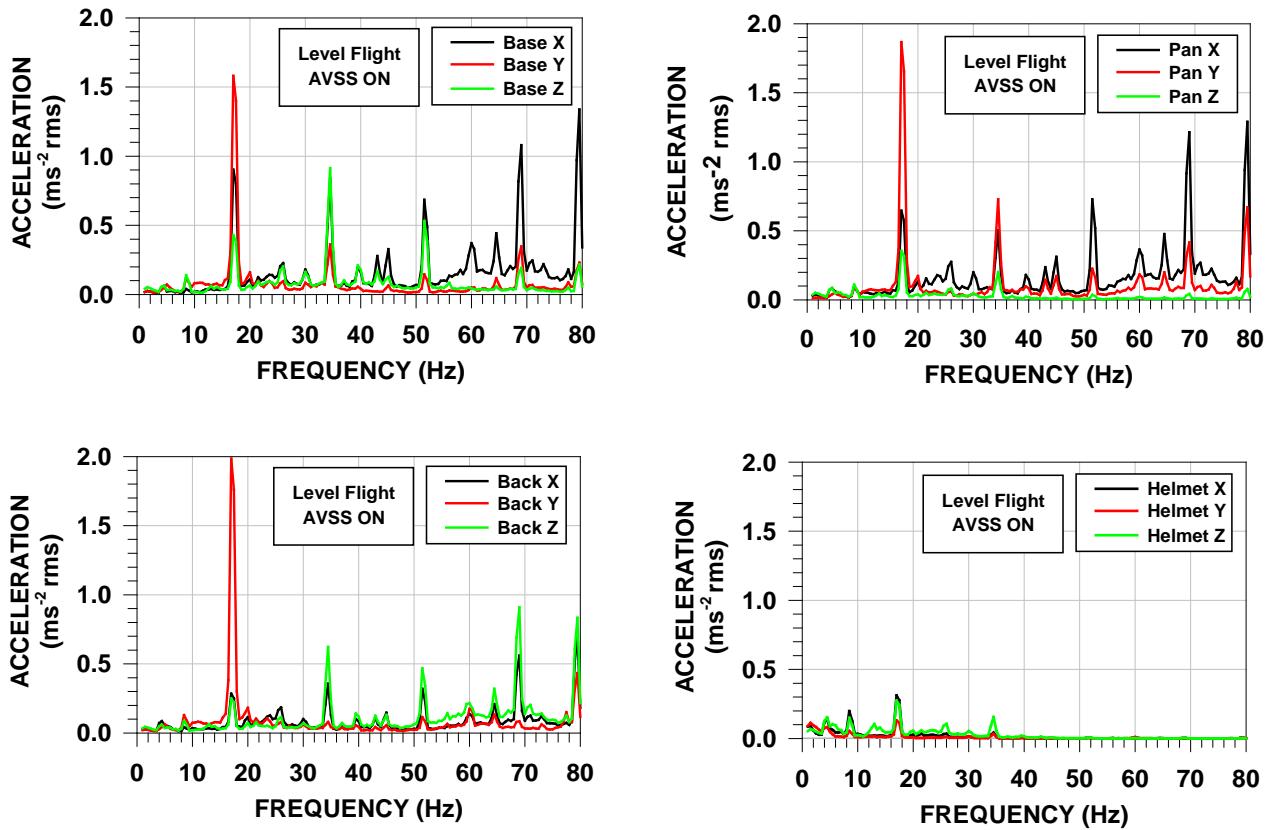


Figure A- 3. HH-60M Level Flight AVSS ON Sample Acceleration

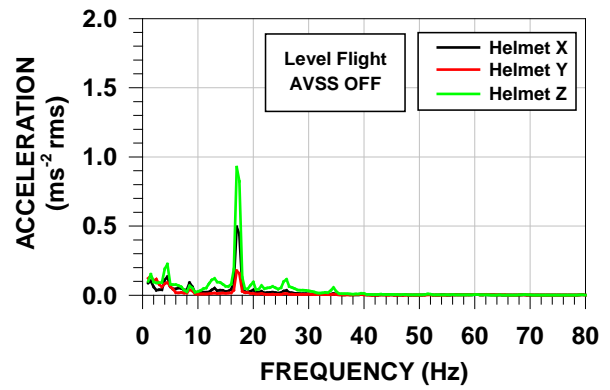
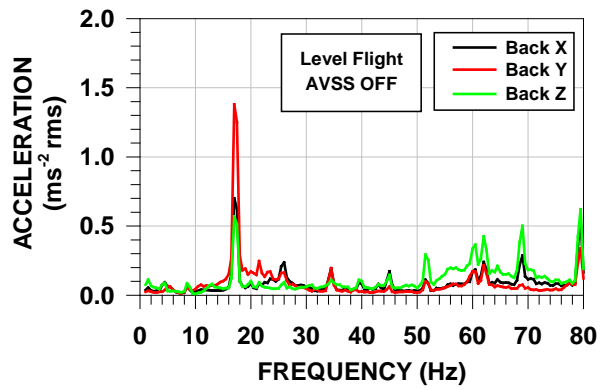
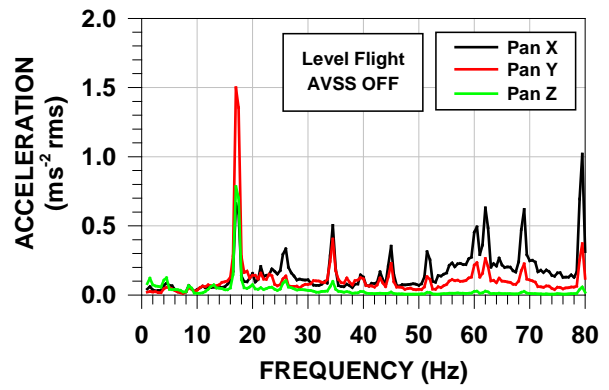
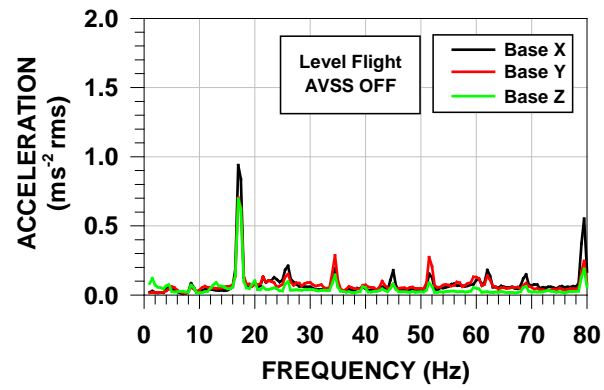


Figure A- 4. HH-60M Level Flight AVSS OFF Sample Acceleration

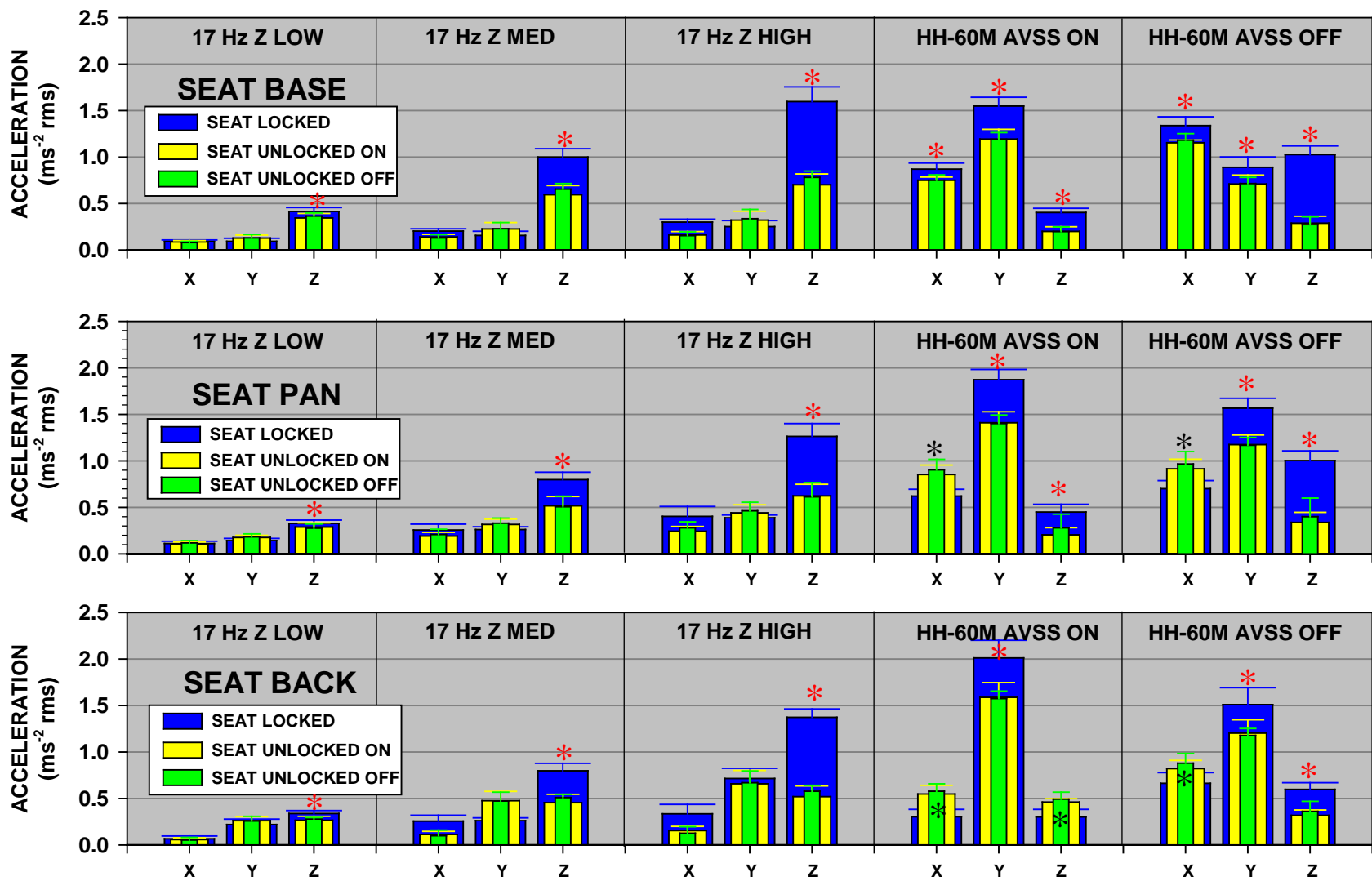


Figure A- 5. Mean 17 Hz Peak Accelerations \pm One Standard Deviation

Those measurement sites and directions showing significant reductions with both UNLOCKED configurations are marked with a red asterisk. Those measurement sites and directions showing a significant increase with both UNLOCKED configurations are marked with a black asterisk.

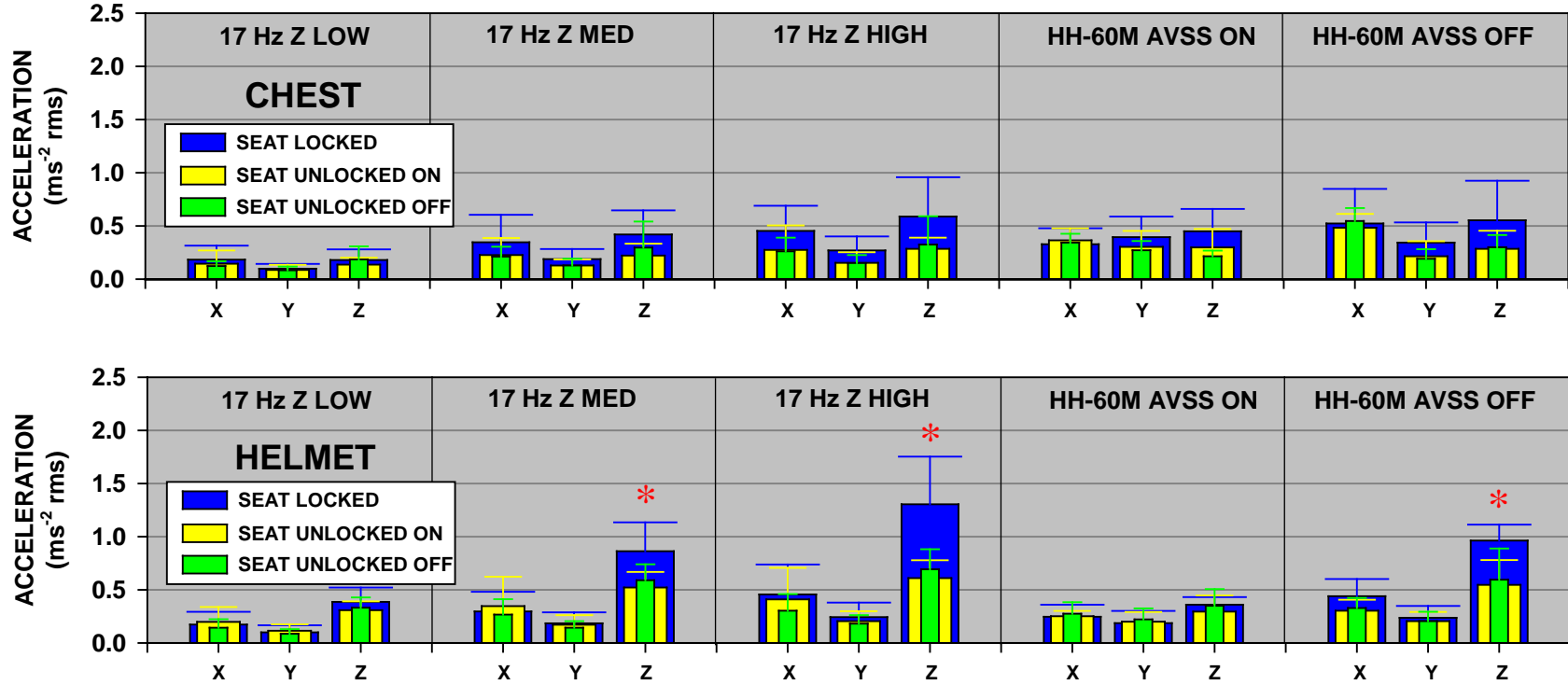


Figure A-5 (continued). Mean 17 Hz Peak Accelerations \pm One Standard Deviation

Those measurement sites and directions showing significant reductions with both UNLOCKED configurations are marked with a red asterisk. Those measurement sites and directions showing a significant increase with both UNLOCKED configurations are marked with a black asterisk.

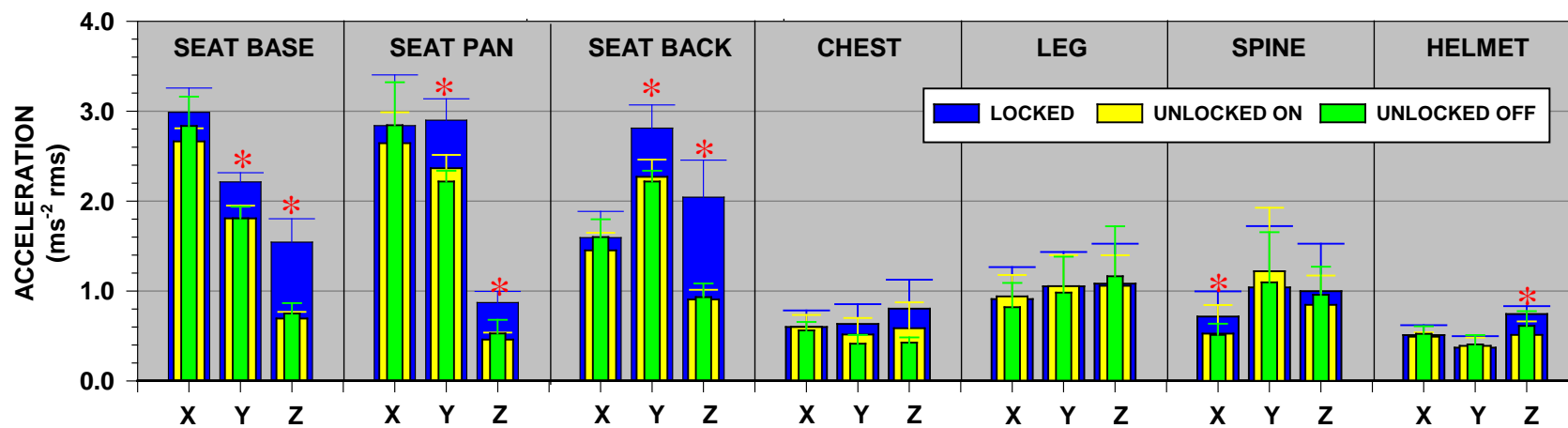


Figure A- 6. Mean HH-60M AVSS ON Unweighted Overall Accelerations
± One Standard Deviation

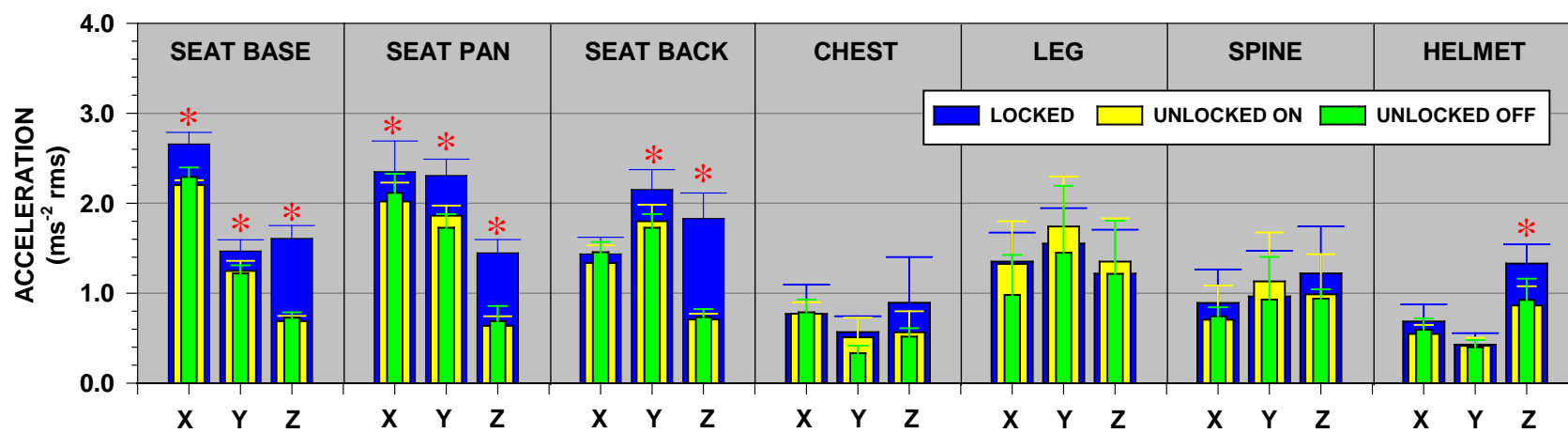


Figure A- 7. Mean HH-60M AVSS OFF Unweighted Overall Accelerations
± One Standard Deviation

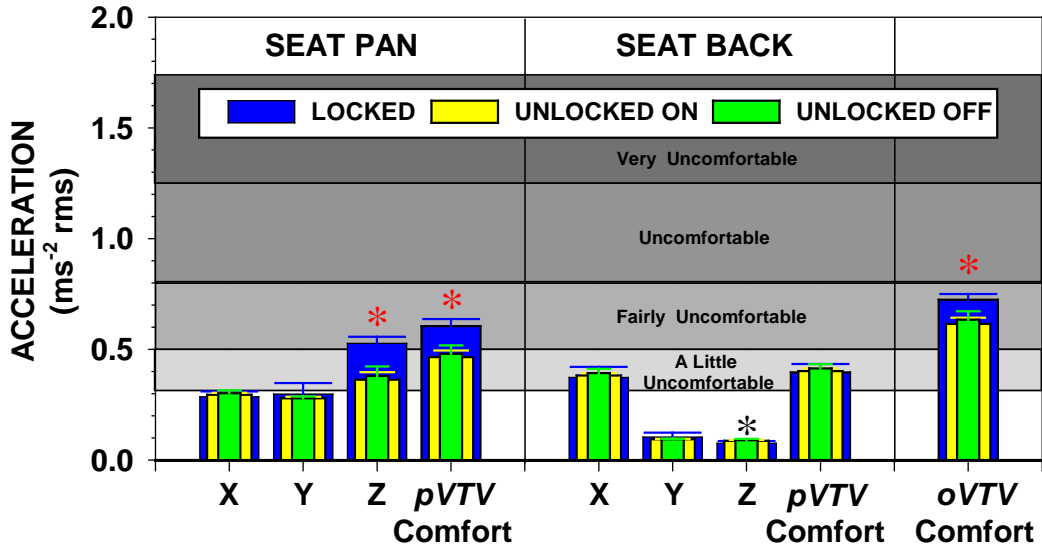


Figure A- 8. Mean HH-60M AVSS ON Weighted Overall Accelerations, *pVTVs* and *oVTV* for Comfort ± One Standard Deviation

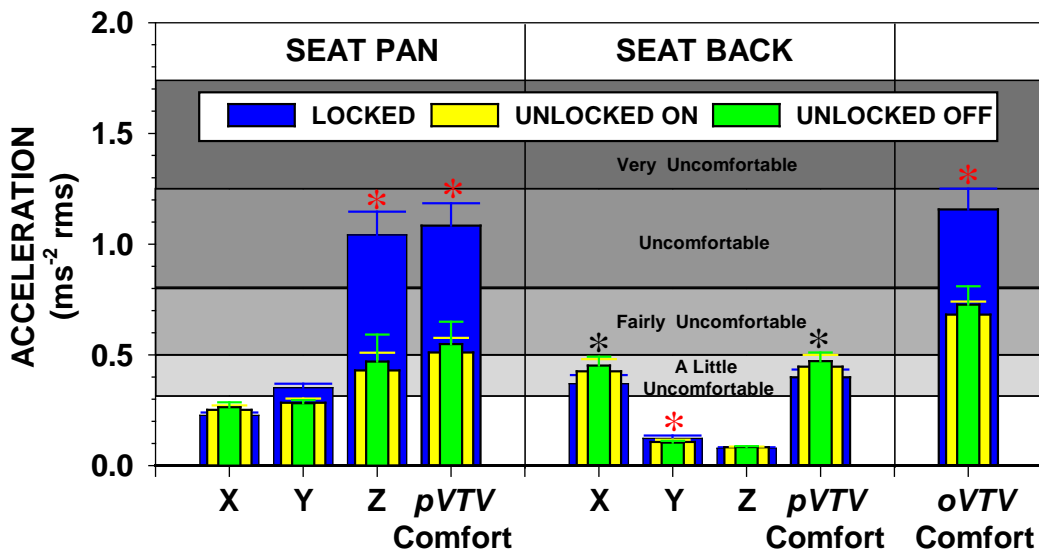


Figure A- 9. Mean HH-60M AVSS OFF Weighted Overall Accelerations, *pVTVs* and *oVTV* for Comfort ± One Standard Deviation

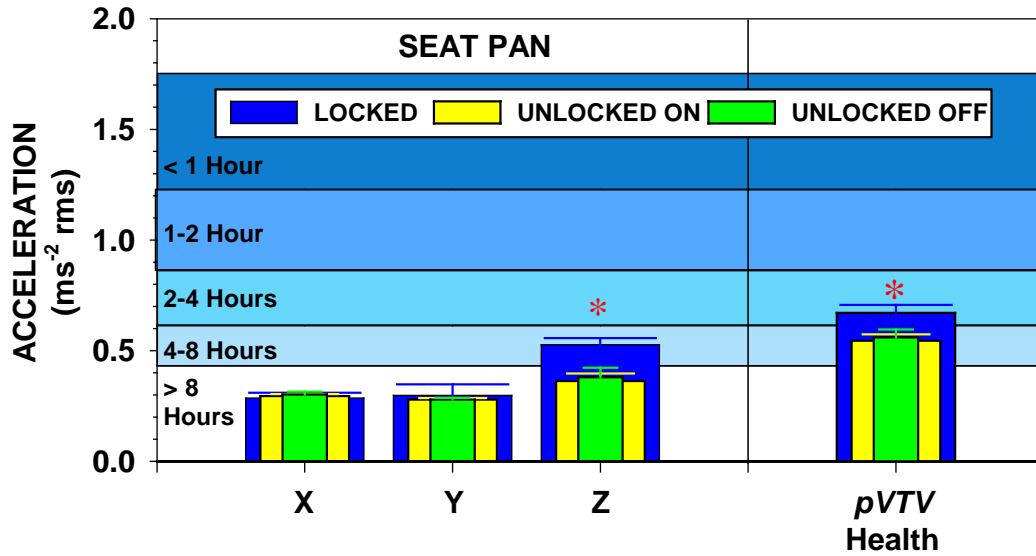


Figure A- 10. Mean HH-60M AVSS ON Weighted Overall Accelerations and *pVTV* for Health Risk \pm One Standard Deviation

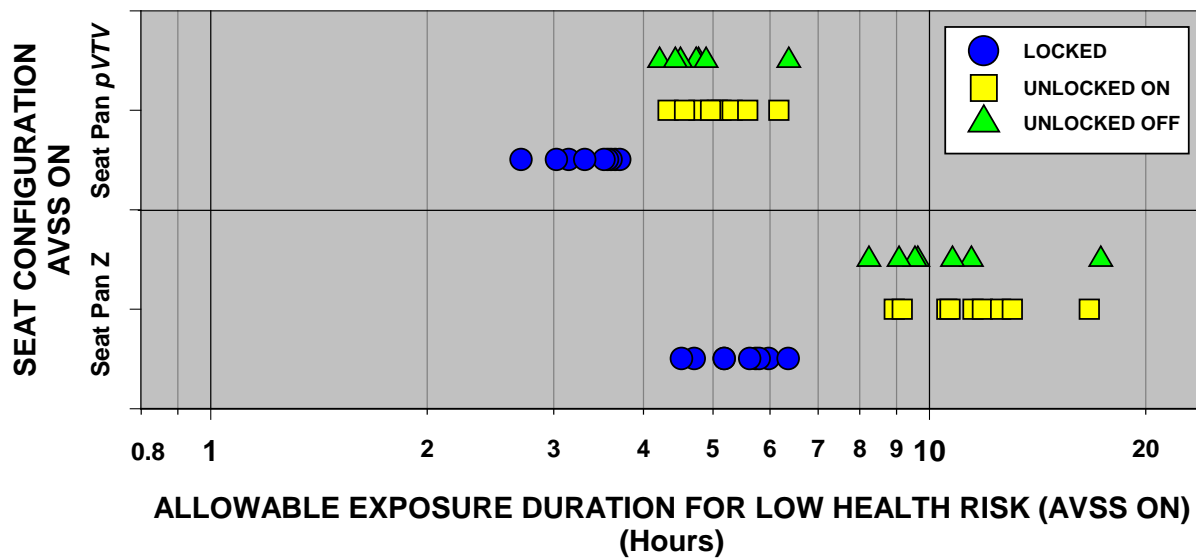


Figure A- 11. Minimum Exposure Durations for Potential Health Risk Using the Weighted Seat Pan Z Acceleration and the Seat Pan *pVTV* for All Subjects (AVSS ON)

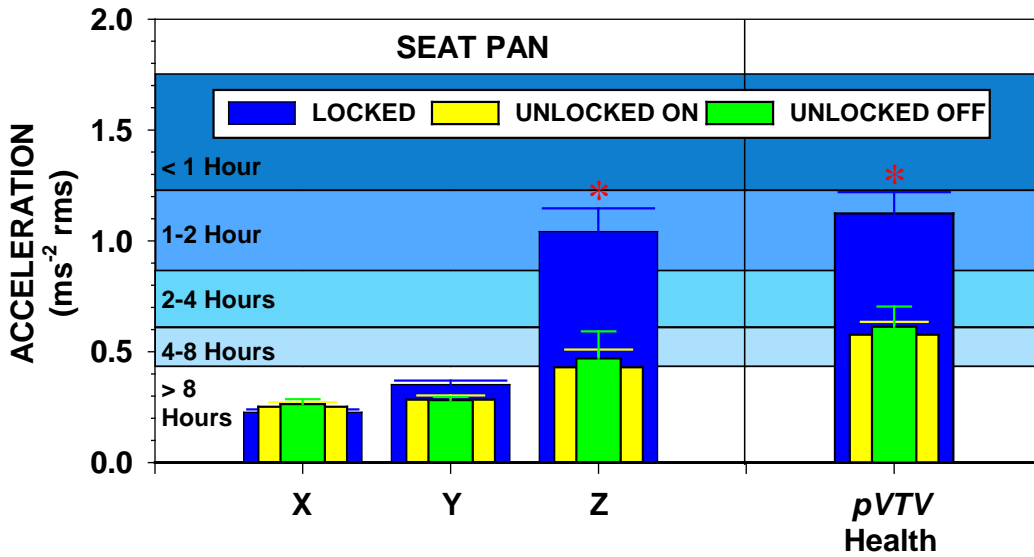


Figure A- 12. Mean HH-60M AVSS OFF Weighted Overall Accelerations and *pVTV* for Health Risk \pm One Standard Deviation

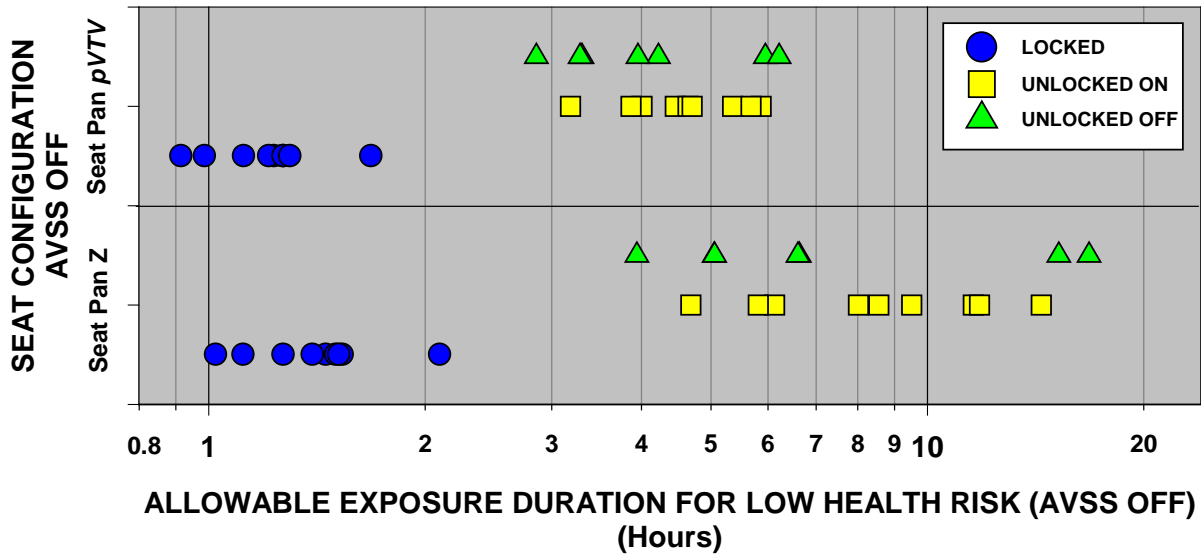


Figure A- 13. Minimum Exposure Durations for Potential Health Risk Using the Weighted Seat Pan Z Acceleration and the Seat Pan *pVTV* for All Subjects (AVSS OFF)

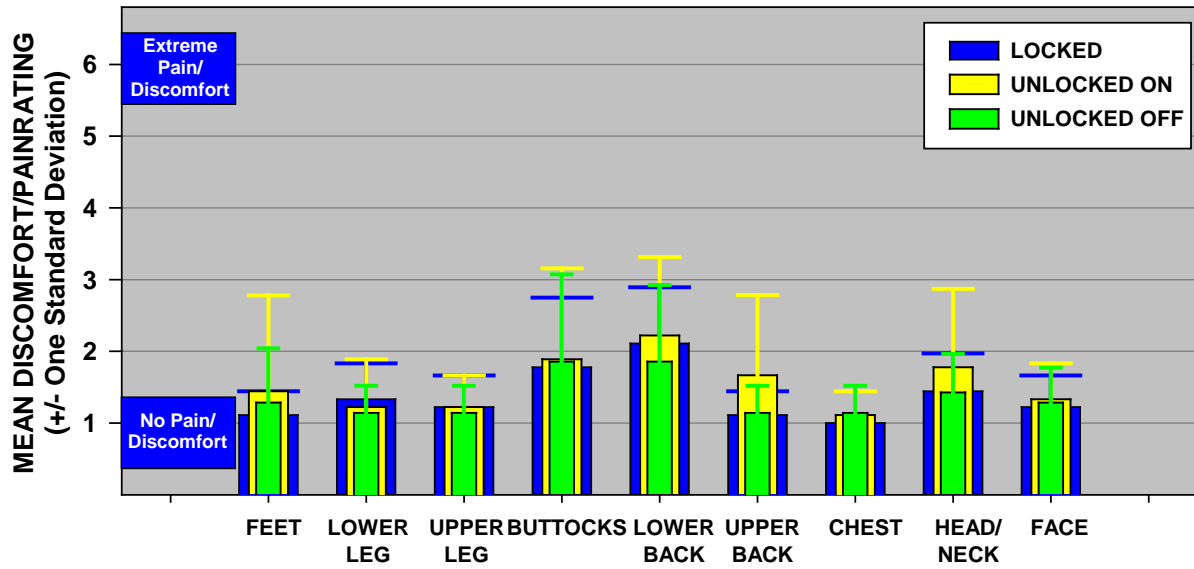


Figure A- 14. Mean Subject Discomfort Rating \pm One Standard Deviation (based on 7 subjects)

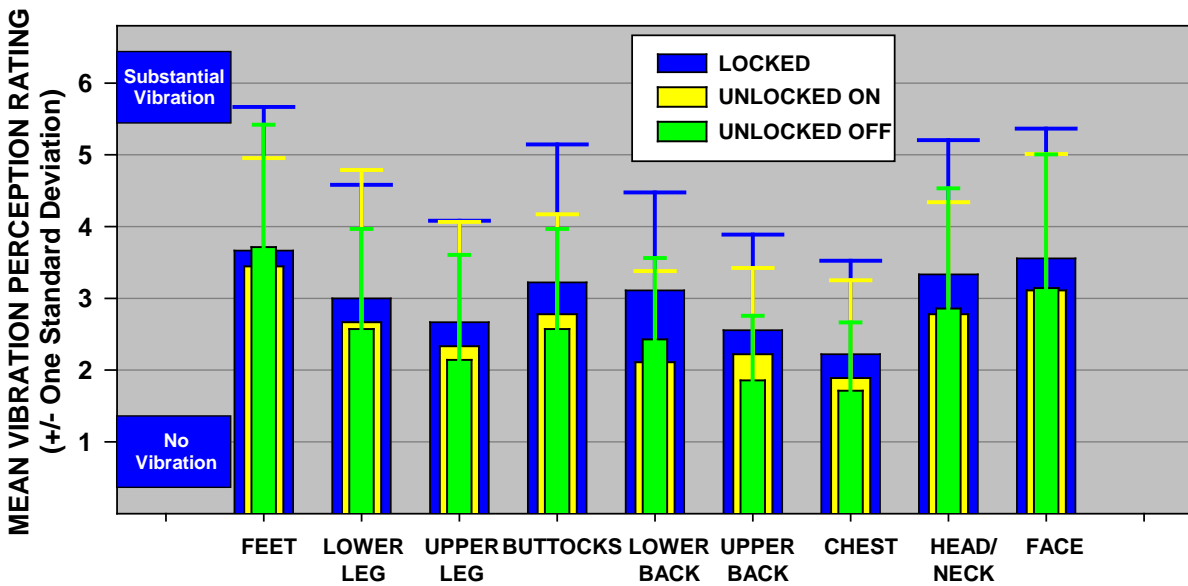


Figure A- 15. Mean Subject Vibration Perception Ratings \pm One Standard Deviation (based on 7 subjects)

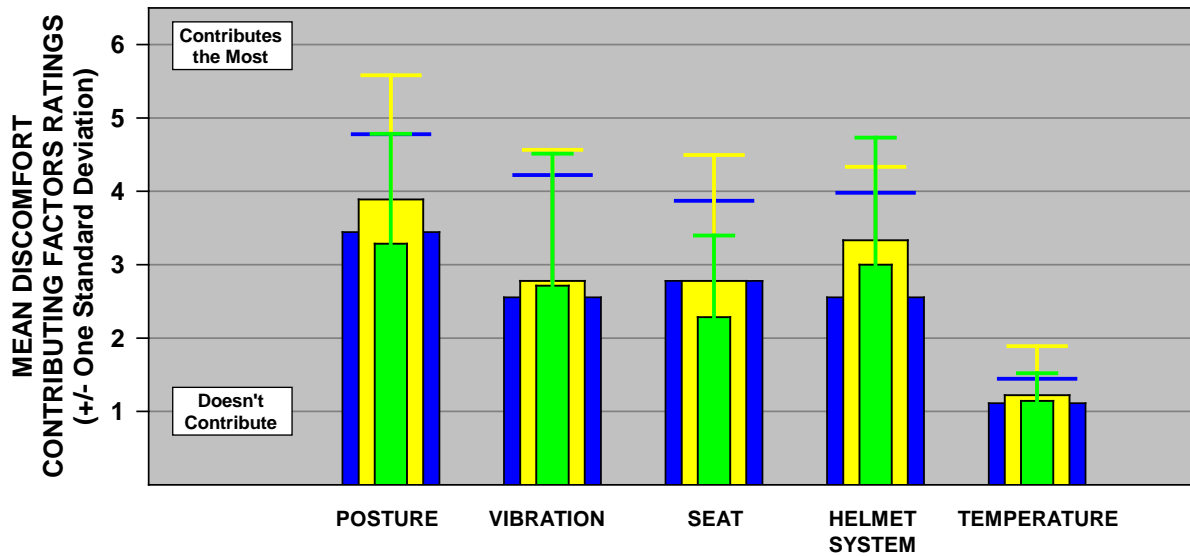


Figure A- 16. Mean Subject Discomfort Contributing Factors Ratings \pm One Standard Deviation (based on 7 subjects)

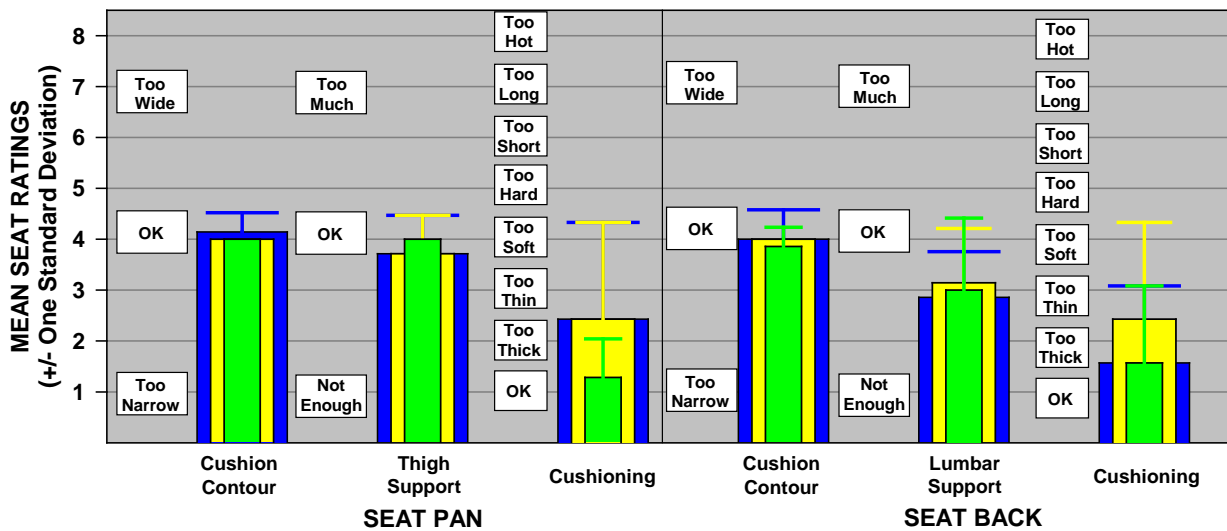


Figure A- 17. Mean Subject Seat Ratings \pm One Standard Deviation (based on 7 subjects)