Amplified Pilot Head Vibration and the Effects of Vibration Mitigation on Neck Muscle Strain

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INTRODUCTION: Rotary wing pilot neck strain is increasing in prevalence due to the combined effects of head supported mass (e.g., Night Vision Goggles, head mounted displays) and whole-body vibration. This study examined the physiological responses of pilots during exposure to whole-body vibration (WBV) representative of the National Research Council's Bell 412 helicopter in forward flight. WBV levels were measured and evaluated using the ISO-2631-1-1997 WBV standards.

METHODS: Twelve pilots (aged 20–59 yr, 7 of the 12 with 20+ years flight experience) underwent six 15-min vibration trials on a human rated shaker platform. Participants were exposed to three vibration levels (-25%, normal, and +25% amplitude; Levels 1–3, respectively) while seated on an Original Equipment Manufacturer (OEM) or vibration mitigating (MIT) cushion. Upper back and neck electromyography (EMG) and acceleration were continuously recorded.

RESULTS: Normalized EMG amplitude was higher using the OEM compared to the MIT during Level 2 (0.18 vs. -0.27) and Level 3 (0.24 vs. -0.14) for the anterior neck muscles. Health weighted vibration amplitude at the head (Mean of 3 levels: OEM = 1.19 and MIT = 1.11 $m \cdot s^{-2}$) was larger than the vibration amplitude at the seat (Mean of 3 levels: OEM = 0.77 and MIT = 0.70 $m \cdot s^{-2}$).

DISCUSSION: The amplification of head vibration relative to the seat, and the significant effects of vibration level, as well as the vibration mitigation cushion, on neck EMG amplitude support the need for revisions to the ISO-2631-1 standard to account for the head and neck response to whole-body vibration.

KEYWORDS: whole-body vibration, electromyography, cushions, helicopter, ISO-2631-1-1997.

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The prevalence of neck strain and discomfort in occupations where workers are exposed to whole-body vibration (WBV), such as aviation (e.g., rotary wing and jet pilots), land transport (e.g., truck drivers), and construction (e.g., equipment operators),[17] is a significant concern not only for operator health but also for operational safety and efficiency. The intensity and duration of whole-body vibration that an individual experiences are key contributors to discomfort and the development of neck pain. While WBV exposure has been reported to have acute adverse health effects (e.g., headache, fatigue, and unsettled stomach), the chronic adverse health effects of repeated and extended exposure to WBV are also of great concern to the rotary wing aviation community.

Long-term health implications of whole-body vibration have been reported to negatively impact the skeletal,[22,25] as well as nervous, vestibular, circulatory, and digestive systems. Repeated and long-term exposure to WBV is associated with degeneration of the spine and the onset of lower back pain, intervertebral degeneration, sciatic pain, and flattening of the lumbar lordosis.[22,25] Moreover, the repetitive compressive force from helicopter vibration increases the load placed on the spine,[10] further contributing to degenerative changes most common in the lumbar region followed by thoracic and cervical changes.[22] Delahye et al.[12] reported that 80% of the pilots who experienced lower back pain also showed spinal abnormalities and degenerative changes in the spine, particularly those pilots with substantial helicopter flight time. As many as 50–75%,[23] 88.1%,[18] and 94%[24] of helicopter pilots indicated neck/back

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pain with variations between pilot groups being due to the number of flight hours, night vision goggle (NVG) and counterweight usage, and mission type. Within the Canadian Forces, Adam[1] found that over 80% of CH-146 Griffon helicopter pilots had neck pain which increased to over 90% when pilots had more than 150 h of NVG experience. Neck pain is a complex issue which may arise due to multiple factors including helmet and NVG masses, increased moments of inertia of the neck, awkward postures and bending, sitting for long periods, high force demands, variations in neck muscle strength, and WBV.[2,7,19]

Lower back and neck pain are among the most commonly reported disabling health problems affecting helicopter pilots. Current seating systems are primarily designed to meet crashworthiness regulations, without accounting for factors that may compromise the health and comfort of pilots, including mission duration, anthropometric differences, and until recently, whole-body vibration mitigation. In recent years, due to increasing awareness of the expansive array of adverse effects associated with WBV, numerous research studies and commercial development efforts have focused on mitigating human vibration exposure.[4,6] The use of seat cushions with vibration mitigating properties has gained increasing interest in the field as a quick solution for vibration-related back and neck pain. For instance, air-inflated cushions, suspension seats, and elastic seats have been examined as vibration mitigation solutions. Seat cushions with novel vibration alleviation properties have been found to be effective in reducing the vibration transmitted through the aircraft floor and seat to the pilot.[4] However, it remains unclear as to the extent to which these cushions reduce neck muscle activity, which is an indicator of muscle fatigue and head vibration.

Vibration mitigation is particularly important for helicopter pilots given that the main rotor vibration is within the range of 4 to 6 Hz (1/rev), which closely matches the resonant frequency of the human spine of 4–5 Hz.[19] Furthermore, amplitudes of vibration within the 4–6 Hz range are magnified at the head.[17] For example, in a recent study, Craig et al.[6] altered the vibration levels of a Bell 412 helicopter by making small changes to the main rotor through a track-and-balance tuning process. Minimal detuning of the main rotor increased the vibration of the helicopter by only 0.006 G, but increased the vibration of the pilot's head by 0.01 G. Although this vibration level was considered safe according to International Organization for Standardization (ISO) 2631-1-1997 (Mechanical Vibration and Shock – Evaluation of human exposure to whole-body vibration), head and neck movements are not taken into account by the current standard.[16] Therefore, given that many of the adverse health effects of WBV occur at ~5 Hz, there is a considerable need for vibration exposure limits outlined in ISO 2631-1-1997 to be revised to incorporate the head and neck, rather than only the trunk, back, and buttocks.

The primary purpose of this study was to examine physiological indicators of neck muscle strain and the effectiveness of a vibration mitigating cushion in helicopter pilots during three levels of whole-body vibration. Physiological and subjective responses were compared during three vibration amplitudes representative of Bell 412 helicopter (Royal Canadian Air Force [RCAF] Griffon) cruise flight with the use of two seat cushions; a standard helicopter cushion (Original Equipment Manufacturer [OEM] cushion) and one with vibration mitigating properties (MIT cushion). Furthermore, exposure to whole-body vibration was evaluated using the acceleration measures and weighting defined in the ISO 2631-1-1997 standard for whole-body vibration. The secondary purpose was to provide further justification for the revision of ISO 2631-1-1997 to incorporate head and neck movements. It was hypothesized that higher neck muscle activation levels (i.e., electromyogram [EMG] amplitudes) and higher head accelerations would coincide with increased levels of vibration and that the vibration mitigating cushion would effectively reduce the vibration transmitted to the pilot at the seat and head.

METHODS

Subjects

Once the study protocol was approved by the National Research Council of Canada's Research Ethics Board, 12 pilots were recruited to participate. All participants were informed of the experimental procedures, risks, and discomforts prior to providing written informed consent. Participants completed a health questionnaire and had their heart rate and blood pressure taken as part of the screening to confirm eligibility and ensure their safety during participation. None of the participants had an on-going history of heart or cardiovascular disease, vestibular disorders, and/or physical activity restrictions. In addition, although none of the participants reported on-going musculoskeletal conditions, some had reported a history of such conditions. The participants were healthy (i.e., free from medical conditions which could potentially be exacerbated by whole-body vibration) men ranging in age from 20–59 yr ($N = 9$ ranging between 45–59 yr of age) with 7 of 12 having 20+ yr of rotary and/or fixed wing flight experience ($N = 1$ with 10–15 yr; $N = 2$ with 5–10 yr; and $N = 2$ with 0–5 yr).

Equipment

NRC's unique Human Rated Shaker (HRS) facility allows accurate reproduction of vehicular (e.g., aircraft–partial or entire flight) vibration in the vertical (z) direction. The HRS platform uses an electro-dynamic mechanical shaker, with four load cells, to replicate the recorded vertical oscillations of vehicle vibration. The use of vertical, or z-axis, vibration simplifies the examination of the human occupant's head movements which are primarily in the longitudinal axis.[17] The HRS mechanical shaker system is capable of reproducing previously recorded vehicle time histories with accelerations up to $10\ \mathrm{m \cdot s^{-2}}$, vibration frequencies from 2 to 1000 Hz, and profiles that include sine sweep, random, random on random, sine dwell, and sine-on-random. Accelerometer placements on the shaker platform and a standard helicopter seat with back allow for the assessment of compliance with the ISO-2631 standard.[16]

The EMG data were recorded by a BioSemi ActiveTwo system (DA-AT-MSADB, BioSemi, Amsterdam, Netherlands) at 2048 Hz. An array of 32 surface EMG electrodes (ActiveTwo flat-type active electrodes, BioSemi, Amsterdam, Netherlands) was used to record muscle activity at 16 locations (i.e., bilateral upper, middle, and lower trapezius, splenius, and sternocleidomastoid muscle sites). All electrodes were affixed to the skin using disposable adhesive disks and SignaGel® electrolyte. A LaserBIRD 2® optical tracker (Ascension Technology Corporation, Shelburne, VT) was used to capture head position and orientation (forward, starboard, down, yaw, pitch, and roll) at 240 Hz.

Miniature Integrated Circuit Piezoelectric (ICP) type accelerometers (ICP Accelerometer 352C22 and ICP Triaxial Accelerometer 356B41, PCB Piezotronics, Depew, NY) were placed on the top of the helmet (triaxial, vibration at the head), on the back rest (triaxial), within a pad on the seat cushion (triaxial, vibration transmitted to the pilot), on the underside of the seat (triaxial), and on the surface of the shaker platform (unidirectional, vertical-axis). Accelerometer data were recorded at 128 Hz by the mechanical shaker control software (SignalStar Matrix Vibration Controller 2.5.1042, Data Physics Corporation, San Jose, CA).

The Karolinska Sleepiness Scale (KSS) was rated on a 9-point scale from 1 (Extremely Alert) to 9 (Extremely sleepy/fighting sleep). The Comfort and Discomfort Scales obtained a rating on a 12-point scale of 0 (No comfort and No discomfort, respectively) to +10 (Extremely strong comfort and Extreme discomfort/almost maximum, respectively) at 9 locations: the neck, left and right shoulder, upper back, lower back, left and right buttock, and left and right thigh.[14]

Procedures

Prior to arriving at the laboratory for the experimental session, each participant was instructed to eat a normal breakfast, and refrain from alcohol and vibration exposure for 12 and 24 h, respectively. Participants were fitted with the electromyography (EMG) electrodes. Participants then donned shoes/light boots and a medical gown over their pants prior to being seated on the aircrew seat of the human rated shaker platform. Participants then donned a prefitted SPH5 (~4 lb) rotary wing helmet (Gentex®, Simpson, PA). Foot pedals were adjusted as per the participants' height and the EMG sensors were connected to the physiological data acquisition system. Participants sat in a flight-realistic posture (i.e., operationally hunched) with their right hand on the simulated cyclic.

All participants completed six experimental trials that consisted of an evaluation of two seat cushions at three vibration levels. An OEM standard helicopter seat cushion and a modified seat cushion containing a vibration mitigating pad (MIT cushion) were evaluated. Low (25% lower amplitude–Level 1, 0.23 G_{rms}), normal (normal amplitude–Level 2, 0.30 G_{rms}), and high (25% higher amplitude–Level 3, 0.36 G_{rms}) vibration levels (**Table I**), representative of ranges observed through rotor track-and-balance tuning, were paired with each cushion for a total of six experimental trials on one experimental day. The Level 2 vibration spectrum corresponded to vibration measurements taken on the floor of NRC's Bell 412 during straight and level flight at 120 knots. Each participant completed a 5-min resting baseline (no vibration) prior to the 6 × 15-min experimental trials, which were each separated by a 15-min recovery (no vibration) period. The 6 experimental trial conditions (vibration level and cushion type) were counterbalanced among the 12 participants.

Electromyography, head position/rotation, and acceleration (floor, seat, cushion, back, and the pilot's head) data were recorded continuously. Neck muscle activation levels were measured using surface EMG to evaluate differences in neck muscle loading while pilots maintained an upright head posture during different WBV and seat cushion conditions. An increase in EMG amplitude, under different WBV levels and/or seat cushions, was taken to indicate an increase in the likelihood of neck muscle strain. Prior to the first vibration exposure, and immediately following each vibration trial, participants provided Karolinska Sleepiness Scale and Localized Comfort/Discomfort Scale ratings.

Raw surface EMG data recordings from each 15-min vibration trial were conditioned and processed in MATLAB (MATLAB R2015a Signal Processing Toolbox, MathWorks®, Natick, MA) as follows: 1) high-pass filtered each electrode channel (10 Hz corner, zero phase, 4th order Butterworth) to remove low-frequency noise caused by electrode impedance changes and movement artifacts; 2) computed the differential EMG signal for each electrode pair; 3) computed the time-resolved power spectral density (PSD) for each differential EMG signal using 1000-ms Hann windows with 500 ms overlap; and 4) compiled the time-resolved PSDs across 5-min epochs within each 15-min vibration trial to compute the median PSD for each trial epoch. Due to WBV-related motion artifacts at harmonics of 5.4 Hz up to 43.2 Hz, EMG signal power below 50 Hz was excluded from EMG amplitude and frequency measures.

EMG amplitude and frequency characteristics depend on muscle fiber type, diameter, and conduction velocity, motor unit discharge rate and synchronization, the distance between muscle fibers and the recording electrode(s), and the low-pass filtering properties of intermediary tissue.[8] Changes in EMG amplitude and frequency measures are often used to study muscle fatigue and force. Muscle fatigue generally coincides with an increase in EMG amplitude and a decrease in median frequency, whereas an increase in muscle force often coincides with higher EMG amplitudes and higher median frequencies.[5] Changes in EMG amplitude and frequency may also occur during nonisometric muscle contractions if the positions of recording electrodes vary with respect to underlying muscle fibers.[9]

Overall EMG root-mean square (RMS) amplitude (i.e., muscle activation level) was computed by integrating the median PSD between 50 Hz to 500 Hz. Because muscle force has been found to be highly correlated with EMG amplitudes above 400 Hz,[20] a second EMG RMS amplitude measure (i.e., EMG force indicator) was derived from the median PSD between 400 Hz and 500 Hz. EMG median frequency was measured as

Table I. Frequency and Amplitude Specifications of the Three Vibration Levels at the Platform Rail.

LEVEL 1 (25% LESS IN AMPLITUDE)										
Background averaged (6×10^{-5} $G^2 \cdot Hz^{-1}$)			**FREQUENCY (HZ)**							
			5.4	**10.8**	**16.2**	**21.6**	**27.0**	**32.4**	**37.8**	**43.2**
Rail	Averaged	G_{rms}	0.023	0.023	0.007	0.077	0.011	0.009	0.008	0.018
	Averaged	G_{peak}	0.032	0.032	0.010	0.108	0.015	0.013	0.011	0.026
LEVEL 2 (NORMAL AMPLITUDE)										
Background averaged (8×10^{-5} $G^2 \cdot Hz^{-1}$)			**FREQUENCY (HZ)**							
			5.4	**10.8**	**16.2**	**21.6**	**27.0**	**32.4**	**37.8**	**43.2**
Rail	Averaged	G_{rms}	0.031	0.031	0.009	0.102	0.014	0.012	0.011	0.024
	Averaged	G_{peak}	0.043	0.043	0.013	0.144	0.020	0.017	0.015	0.034
LEVEL 3 (25% MORE IN AMPLITUDE)										
Background averaged (1×10^{-4} $G^2 \cdot Hz^{-1}$)			**FREQUENCY (HZ)**							
			5.4	**10.8**	**16.2**	**21.6**	**27.0**	**32.4**	**37.8**	**43.2**
Rail	Averaged	G_{rms}	0.039	0.039	0.011	0.128	0.018	0.015	0.014	0.030
	Averaged	G_{peak}	0.054	0.054	0.016	0.180	0.025	0.021	0.019	0.043

the frequency at which the median PSD integral between 50 Hz and 500 Hz reached its 50th percentile. For each EMG metric (overall amplitude, force indicator, and median frequency), a total of 18 measurements were taken per EMG recording site across 2 cushions, 3 vibration levels, and 3 epochs per trial. To enable pooling of EMG measures across recording sites and across study participants, each set of 18 values was normalized by removing outliers (i.e., individual data points more than 2.5 $\times$ interquartile range below the 25th percentile or above the 75th percentile) and then subtracting the mean and dividing by the standard deviation. The resulting data set for each EMG metric consisted of normalized values with mean $= 0$ and standard deviation $= 1$.

Head and neck movements were unconstrained while participants were actively engaged in a target-tracking task for the duration of the session. The task included a point tracking task with a joystick connected with a video monitor screen directly in front of them and they were required to maintain the cross-hair template over the moving target for measuring error, missed targets, and response latency. The tracking task was utilized to keep the participant engaged in a flight related task with their right hand on a simulated cyclic (joystick).

Changes in head position and orientation during each trial coincided with nonisometric neck muscle contractions that affected EMG amplitude and frequency measures. To remove the variance associated with nonisometric muscle contractions, normalized EMG measures (amplitude, median frequency, and force indicator) for each EMG site were regressed against the six degrees of freedom of head position (forward, starboard, and vertical) and orientation (yaw, pitch, and roll). The multivariate regression model included linear, interaction, and quadratic terms to capture both linear and nonlinear correlations between EMG measures and head degrees-of-freedom. Separate regression models were applied for the two cushions due to differences in absolute head position and orientation (e.g., average vertical head position was 2.2 cm lower with the OEM than the MIT cushion). Residuals from each regression model, which represented the variance in EMG measures that was unaccounted for by variations in head/neck posture across trials and epochs, were then evaluated for the main effects and interactions of cushion/level and trial/epoch on neck muscle activation during vibration trials.

As an indicator of muscle fatigue (i.e., increase in EMG amplitude and a decrease in median frequency[5]), the average delta amplitude and average delta frequency were calculated over all EMG measures as Epoch 3 minus Epoch 1.

Statistical Analysis

A two-way analysis of variance (ANOVA) with repeated measures of Vibration Level (Level 1, Level 2, Level 3) and Cushion type (OEM, MIT) was performed separately on electromyography (EMG amplitude, median frequency, force indicator), and seat and head vibration amplitude. Each 15-min vibration session was segmented into 3 epochs for analysis, and a second two-way ANOVA was then performed on the 6 trials to detect effects of trial (time-in-session) and epoch (time-in-trial). For significant main effects or interactions detected by repeated measures ANOVA, P values with Greenhouse-Geisser adjustment are reported. For the subjective measures, the Friedman's test was used to test for main effects of Vibration Level, Cushion type, and Trial on ratings of sleepiness, comfort, and discomfort. In addition, the Friedman's test was used to test for the effect of body segment (e.g., neck, upper back, lower back) on localized comfort and discomfort. When a significant F-ratio was obtained, a Tukey's Honest Significant Difference (HSD) post hoc procedure was used to isolate differences. While the EMG and acceleration measures did not pass the Henze-Zirkler's Multivariate Normality Test, the cause was due to varying degrees of skewness and not due to outliers. In all cases, significance was reported when $P \leq 0.05$. Statistical analysis was completed in MATLAB (MATLAB R2015a Statistics and Machine Learning Toolbox, MathWorks®, Natick, MA).

RESULTS

Normalized EMG measures were divided into three groups based on electrode placement: anterior neck muscle fibers (left and right inferior and superior sternocleidomastoid), posterior neck muscle fibers (left and right splenius, left and right superior and inferior upper trapezius), and shoulder muscle fibers (left and right lateral upper and middle trapezius). For anterior neck muscle fibers, a significant Vibration Level $\times$ Cushion interaction was detected for the EMG amplitude [$F(2,22) = 3.80$, $P = 0.043$] in addition to a significant main effect of Cushion type [$F(1,11) = 10.50$, $P = 0.008$] (**Fig. 1A**). Post hoc testing revealed that anterior neck EMG amplitudes were significantly higher with the OEM cushion than the MIT cushion during Vibration Levels 2 and 3. Moreover, anterior neck EMG amplitudes were significantly lower during Vibration Level 1 compared to Vibration Level 2 on the MIT cushion. In addition, a significant main effect of Epoch [$F(2,20) = 4.99$, $P = 0.025$] was detected for anterior neck EMG amplitude, with significantly higher EMG amplitudes during Epoch 2 than Epoch 1. For posterior neck muscle fibers, a significant main effect of Vibration Level was detected for EMG amplitude [$F(2,22) = 3.54$, $P = 0.047$], with significantly higher EMG amplitudes recorded during Vibration Level 3 compared to Vibration Level 1. For shoulder muscle fibers, significant main effects of Vibration Level [$F(2,22) = 4.18$, $P = 0.030$] and Cushion type [$F(1,11) = 13.42$, $P = 0.004$] were detected for EMG amplitude (**Fig. 1B**), with significantly higher EMG amplitudes with the OEM cushion compared to the MIT cushion and significantly lower EMG amplitudes during Vibration Level 1 than Vibration Level 2. No significant main effects of Trial or Epoch were detected for posterior neck or shoulder EMG amplitudes.

EMG median frequency for anterior neck muscle fibers showed a Vibration Level $\times$ Cushion interaction [$F(2,22) = 9.30$, $P = 0.002$] as well as a main effect of Cushion type [$F(1,11) = 7.12$, $P = 0.022$] (**Fig. 1C**). Anterior neck EMG median frequency was significantly lower for the OEM cushion than the MIT cushion during Vibration Level 3 and lower during Vibration Level 1 compared to Level 3 for the MIT cushion. No significant main effects of Trial or Epoch on anterior neck EMG median frequency were observed. For posterior neck, EMG median frequency showed no significant main effects of Vibration Level, Cushion, Trial, or Epoch. For shoulder EMG median frequency, a significant main effect of Cushion type [$F(1,11) = 12.35$, $P = 0.005$] was detected (**Fig. 1D**), with significantly lower median frequencies detected for the OEM cushion compared to the MIT cushion. In addition, a significant main effect of Epoch [$F(2,22) = 6.54$, $P = 0.016$] was detected for posterior neck median frequency; significantly higher median frequencies were detected during Epoch 1 than during Epoch 2.

The EMG force indicator metric (i.e., EMG amplitude between 400–500 Hz) for anterior neck muscle fibers showed no significant main effects of Vibration Level or Cushion type (**Fig. 1E**). For posterior neck muscle fibers, a significant main effect of Vibration Level was detected for EMG force indicator [$F(2,22) = 5.19$, $P = 0.018$]. EMG force indicator was significantly higher during Vibration Level 3 compared to Vibration Level 1. For shoulder muscle fibers, a significant main effect of Cushion type was detected (**Fig. 1F**). Post hoc testing revealed that EMG force indicator was higher for the OEM cushion than the MIT cushion for shoulder muscle fibers. No significant main effects of Trial or Epoch on EMG force indicator were detected for anterior neck, posterior neck, or shoulder muscle fibers.

To evaluate whether EMG recordings showed evidence of muscle fatigue within 15-min vibration exposures, the differences in normalized EMG amplitude and normalized median frequency were computed from Epoch 3 to Epoch 1. Over all EMG recordings, the average delta amplitude and average delta frequency revealed that neck muscle activity generally shifted toward higher amplitudes and lower frequencies, indicative of muscle fatigue, during 15-min vibration exposures (**Fig. 2**).

When weighted for health according to ISO-2631-1-1997, seat pad acceleration showed a Vibration Level x Cushion type interaction [$F(2,22) = 5.33$, $P = 0.020$] as well as main effects of both Vibration Level ($F(2,22) = 198.09$, $P < 0.001$) and Cushion type [$F(1,11) = 27.00$, $P < 0.001$] (**Fig. 3A**). Post hoc testing revealed that health-weighted seat acceleration was significantly lower with the MIT cushion compared to the OEM cushion for all three Vibration Levels. For both cushions, health-weighted seat acceleration was significantly higher during Vibration Levels 2 and 3 compared to Vibration Level 1 and during Vibration Level 3 compared to Vibration Level 2.

Although ISO-2631-1-1997 health weightings are only applicable to the seat interface data in the current study, acceleration at the head was weighted for health using the same ISO weighting algorithms given the lack of other standards for head vibration. Acceleration at the head showed main effects of Vibration Level [$F(2,22) = 122.32$, $P < 0.001$] and Cushion type [$F(1,11) = 11.86$, $P = 0.005$] and was greater than seat vibration during all conditions (**Fig. 3B**). Health-weighted head acceleration was significantly lower with the MIT cushion compared to the OEM cushion. Head acceleration was significantly higher during Vibration Levels 2 and 3 compared to Vibration Level 1 and significantly higher during Vibration Level 3 compared to Vibration Level 2. The MIT cushion reduced the acceleration at the head by 4.6, 6.7, and 8.0% for Vibration Levels 1, 2, and 3, respectively (overall 6.6% average reduction).

Vibration exposure curves for health risk, according to ISO 2631-1-1997, are plotted in **Fig. 4**. Based on seat pad acceleration, the use of the MIT cushion extended the minimal risk exposure duration by 32.8, 36.2, and 34.2 min for Vibration Levels 1, 2, and 3, respectively. Based on head acceleration, the use of the MIT cushion extended the minimal risk exposure duration by 7.5, 5.0, and 3.9 min for Vibration Levels 1, 2, and 3, respectively. The MIT cushion reduced the acceleration at the seat by 6.2, 7.7, and 12.7% for Vibration Levels 1, 2, and 3, respectively (overall 9.3% average reduction) compared to the OEM cushion.

Acceleration at the seat pad showed, when weighted for comfort according to ISO-2631-1-1997, a Vibration Level x Cushion type interaction [$F(2,22) = 6.13$, $P = 0.011$] as well as main effects of Vibration Level [$F(2,22) = 164.47$, $P < 0.001$] and Cushion type [$F(1,11) = 28.63$, $P < 0.001$] (**Fig. 3C**). Comfort-weighted seat acceleration was significantly lower with the MIT cushion compared to the OEM cushion for all three Vibration Levels. For both cushions, comfort-weighted seat acceleration was significantly higher during Vibration

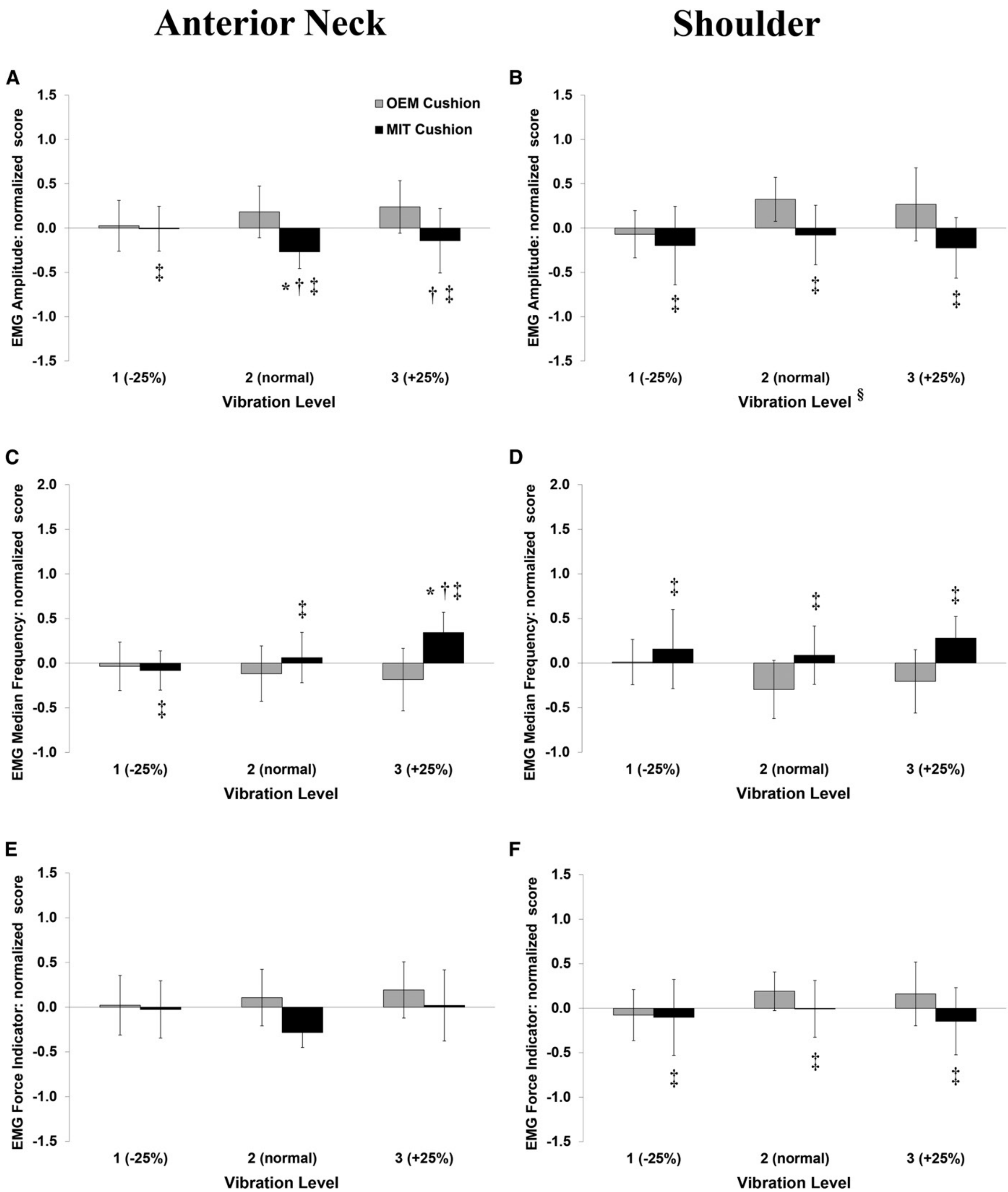

Fig. 1. EMG amplitude, median frequency, and force indicator of normalized data for the anterior neck muscles (upper left A, middle left C, and lower left E, respectively) and shoulder muscles (upper right B, middle right D, lower right F, respectively) over the 15-min vibration exposures for the three vibration levels (1: -25%; 2: normal; and 3: +25% amplitude) when using the original standard cushion (OEM; grey) and vibration mitigating cushion (MIT; black). Anterior muscles include the left and right inferior and superior sternocleidomastoid and the shoulder muscles include the left and right lateral upper and middle trapezius muscles. Values are mean ± SD. *Significantly different than Vibration Level 1; †Significantly different than OEM; ‡Main effect of cushion type; §Main effect of vibration level.

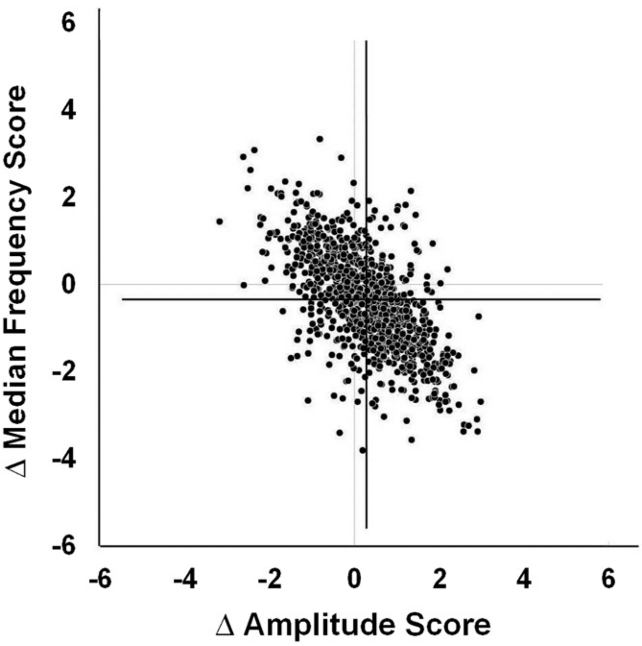

Fig. 2. Delta median frequency versus the delta amplitude scores for all EMG. Black solid line indicates the average delta scores (Epoch 3 – Epoch 1) on the two axes.

Levels 2 and 3 compared to Vibration Level 1 and during Vibration Level 3 compared to Vibration Level 2. The MIT cushion reduced the acceleration at the seat by 6.3, 8.7, and 13.5% for Vibration Levels 1, 2, and 3, respectively (overall 10.0% average reduction).

Given the lack of vibration standards which incorporate the head, when the comfort weightings of ISO-2631 were applied to the head acceleration data, acceleration at the head showed main effects of Vibration Level [$F(2,22) = 123.79$, $P < 0.001$] and Cushion type [$F(1,11) = 16.12$, $P = 0.002$] and was greater than seat vibration during all conditions (**Fig. 3D**). Comfort-weighted head acceleration was significantly lower with the MIT compared to the OEM cushion. Head acceleration was significantly higher during Vibration Levels 2 and 3 compared to Level 1 and during Vibration Level 3 compared to Level 2. The MIT cushion reduced the acceleration at the head by 5.4, 7.7, and 9.0% for Vibration Levels 1, 2, and 3, respectively (overall 7.6% average reduction). No main effects of Trial or Epoch were observed for health or comfort weighted acceleration at the seat pad or head.

The transmission of vibration to the head, as measured by a calibrated triaxial accelerometer placed on the top of the helmet, was amplified compared to the seat pad when using the OEM cushion and to a lesser extent when using the vibration mitigating cushion during Vibration Levels 1 and 2 when weighted for comfort (Δ Head-Seat; Level 1 OEM = 0.338 and MIT = 0.325 $m \cdot s^{-2}$, Level 2 OEM = 0.407 and MIT = 0.383 $m \cdot s^{-2}$) and health (Δ Head-Seat; Level 1 OEM = 0.377 and MIT = 0.368 $m \cdot s^{-2}$, Level 2 OEM = 0.444 and MIT = 0.421 $m \cdot s^{-2}$). At the highest vibration level, head acceleration was still greater than seat pad acceleration for both comfort (Δ Head-Seat; OEM = 0.403 and MIT = 0.407 $m{\cdot}s^{-2}$) and health (Δ Head-Seat; OEM = 0.441 and MIT = 0.449 $m{\cdot}s^{-2}$) weighted acceleration.

No significant differences were observed between the OEM and MIT cushions or between Vibration Level 1 (OEM = 3.9 ± 1.4, MIT = 5.2 ± 1.9), Level 2 (OEM = 4.3 ± 1.5, MIT = 4.3 ± 2.1), and Level 3 (OEM = 4.9 ± 1.8, MIT = 4.8 ± 1.5) for the Karolinska Sleepiness Scale. A main effect of Trial number was observed for the Karolinska Sleepiness Scale [$\chi^2(5,55) = 13.17$, $P = 0.022$], with sleepiness increasing across trials (i.e., sleepiness rating was significantly higher during Trial 5 than Trial 1). Similarly, no significant differences were observed between the OEM and MIT cushions or between Vibration Level 1 (OEM = 5.3 ± 2.8, MIT = 5.2 ± 2.8), Level 2 (OEM = 5.2 ± 2.8, MIT = 5.5 ± 2.8), and Level 3 (OEM = 5.4 ± 3.0, MIT = 5.1 ± 2.6) for comfort rating. A main effect of Trial number was observed for the comfort rating [$\chi^2(5,55) = 17.64$, $P = 0.003$], indicative of decreasing comfort over the duration of the 6 experimental trials (i.e., comfort was reduced following Trial 6 compared with Trial 1). Furthermore, a main effect of Location was observed for comfort rating [$\chi^2(8,88) = 20.49$, $P = 0.009$], with post hoc analysis revealing significantly less comfort at the buttock relative to the thigh. For the discomfort rating, no significant differences were observed between the OEM and MIT cushions or between Vibration Level 1 (OEM = 1.3 ± 0.6, MIT = 1.2 ± 0.7), Level 2 (OEM = 1.4 ± 0.8, MIT = 1.1 ± 0.5), and Level 3 (OEM = 1.1 ± 0.5, MIT = 1.3 ± 0.8). A main effect of Trial was detected ($\chi^2(5,55) = 15.94$, $P = 0.007$), with post hoc testing revealing significantly higher discomfort after Trial 6 than after Trial 1. A main effect of Location was also detected [$\chi^2(8,88) = 20.59$, $P = 0.008$], with significantly higher discomfort at the buttocks than the thigh.

DISCUSSION

The current study demonstrated that relatively small changes in the vibration level resulted in changes in neck muscle activity and head acceleration. The study also showed that the use of a vibration mitigating cushion was effective in reducing neck muscle activation. The transmission of vibration to the head, as measured by helmet acceleration, was amplified compared to the seat pad when using the OEM cushion and to a lesser extent when using the vibration mitigating cushion during Vibration Levels 1 and 2 when weighted for comfort and health. At the highest vibration level, head acceleration was still greater than seat pad acceleration for both comfort and health weighted acceleration. The ISO-2631-1-1997 exposure limits are based on seat pad vibration exposure and do not take head acceleration into account. Thus, the amplification of vibration at the head compared to the seat raises health, safety, and comfort concerns for pilots with regards to neck strain and injury potential.

An increase in muscle fatigue has been shown to generally correlate with increases in EMG amplitudes and decreases in EMG frequencies, whereas decreases in EMG amplitudes and increases in EMG frequencies are seen with increasing muscle

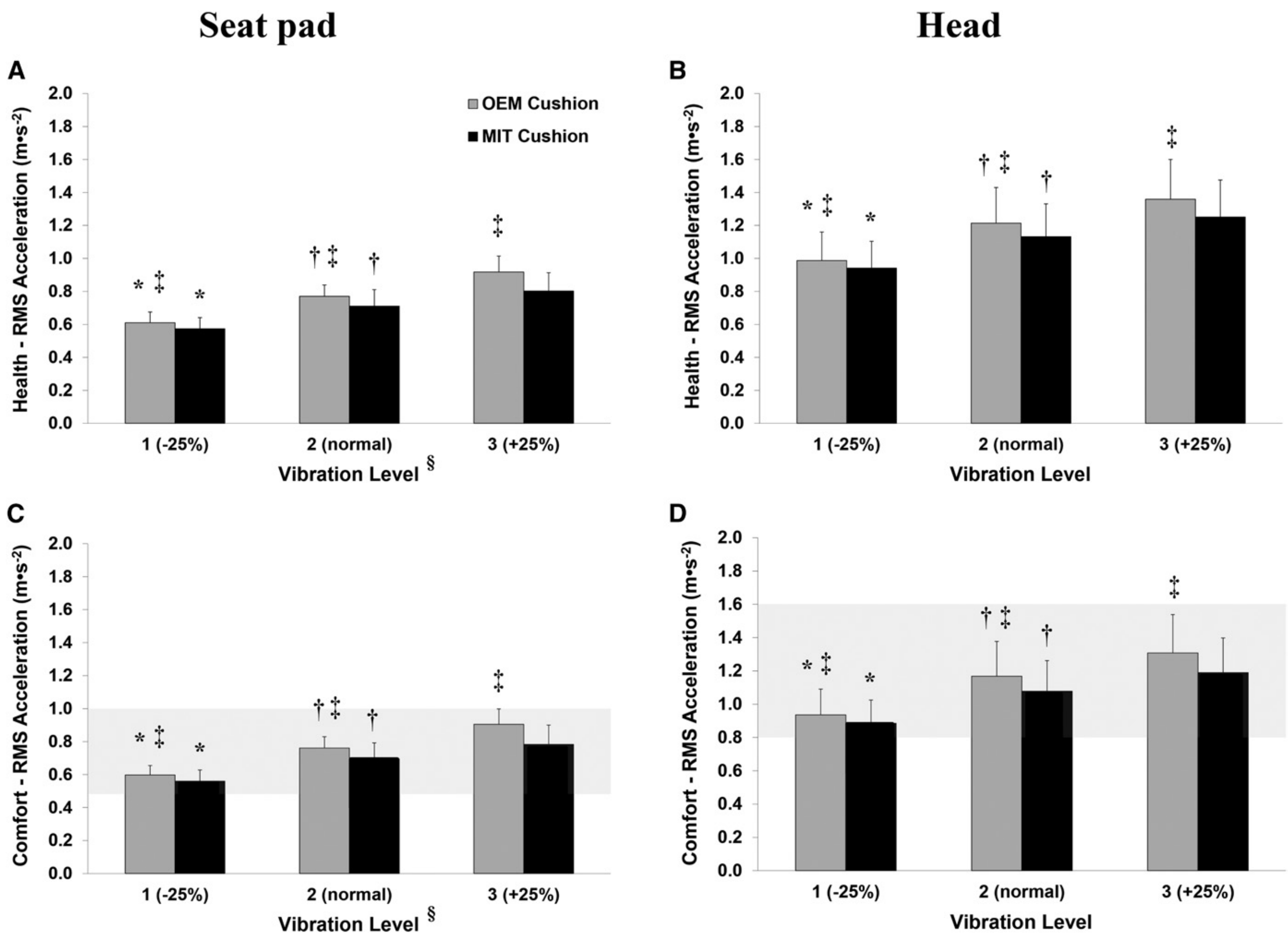

Fig. 3. ISO-2631 seat pad health (upper left A) and comfort (lower left C) weighted acceleration and estimated head health (upper right B) and comfort (lower right D) weighted acceleration over the 15-min vibration exposures for the three vibration levels (1: -25%; 2: normal; and 3: +25% amplitude) when using the original standard cushion (OEM; grey) and vibration mitigating cushion (MIT; black). Values are mean ± SD. *Significantly different than Vibration Levels 2 and 3, †Significantly different than Vibration Level 3, ‡Significantly different than MIT, §Significantly different than Head Acceleration. Gray shading represents "Fairly Uncomfortable" (0.5–1.0 $m \cdot s^{-2}$) range for the seat pad (C) and "Uncomfortable" (0.8–1.6 $m \cdot s^{-2}$) range for the head (D) according to ISO-2631-1-1197.

force and/or muscle recovery.[5] In the current study, higher EMG amplitudes and lower median frequencies were observed with increasing vibration levels while sitting on the OEM cushion. Contrary to a study by de Oliveira et al.[11] which reported no causal effect between EMG and vibration at the erector spine muscle with low EMG levels during most of a real flight duration, the current study in which EMG amplitudes increased with vibration is consistent with Santos et al.,[21] who reported an increase in seated back muscle activity with vibration compared to no vibration. Interestingly, participants in the de Oliveira et al.[11] study and the current study had a backrest available for use during the study, whereas participants in the Santos et al.[21] study were not permitted to use the back rest. Furthermore, EMG muscle force measures (i.e., EMG power above 400 Hz) in the current study indicated higher force muscle contractions with increasing vibration level, contributing to elevated neck strain and muscle fatigue. With the MIT cushion, however, significant differences in EMG amplitude between vibration levels were only detected between the lowest and highest vibration levels. At higher vibration levels, lower EMG amplitudes and higher median frequencies, suggestive of less neck strain, were recorded with the MIT cushion compared to the OEM cushion. Relative differences in EMG amplitude, median frequency, and force indicators indicate that the higher level of vibration or use of the OEM cushion may coincide with higher muscle fatigue and neck strain than lower levels of vibration when using the vibration MIT cushion.

A similar pattern of response regarding an average increase in EMG amplitude and an average decrease in EMG median frequency was also observed for all EMG muscle sites measured over the duration of the full experimental session. Specifically, all left side trapezius and splenius capitis muscle fibers, the side opposite to the arm used to perform a tracking and vigilance task, were the most sensitive to effects of vibration level as measured through EMG amplitude and median frequency. This is consistent with a study of Coast Guard helicopter pilots where fatigue in the right trapezius, due to flying, was significantly correlated with average flight duration, total service of pilot, pain, and total flying hours.[3] Similarly, the trapezius muscles showed an increase in metabolic stress when wearing NVG

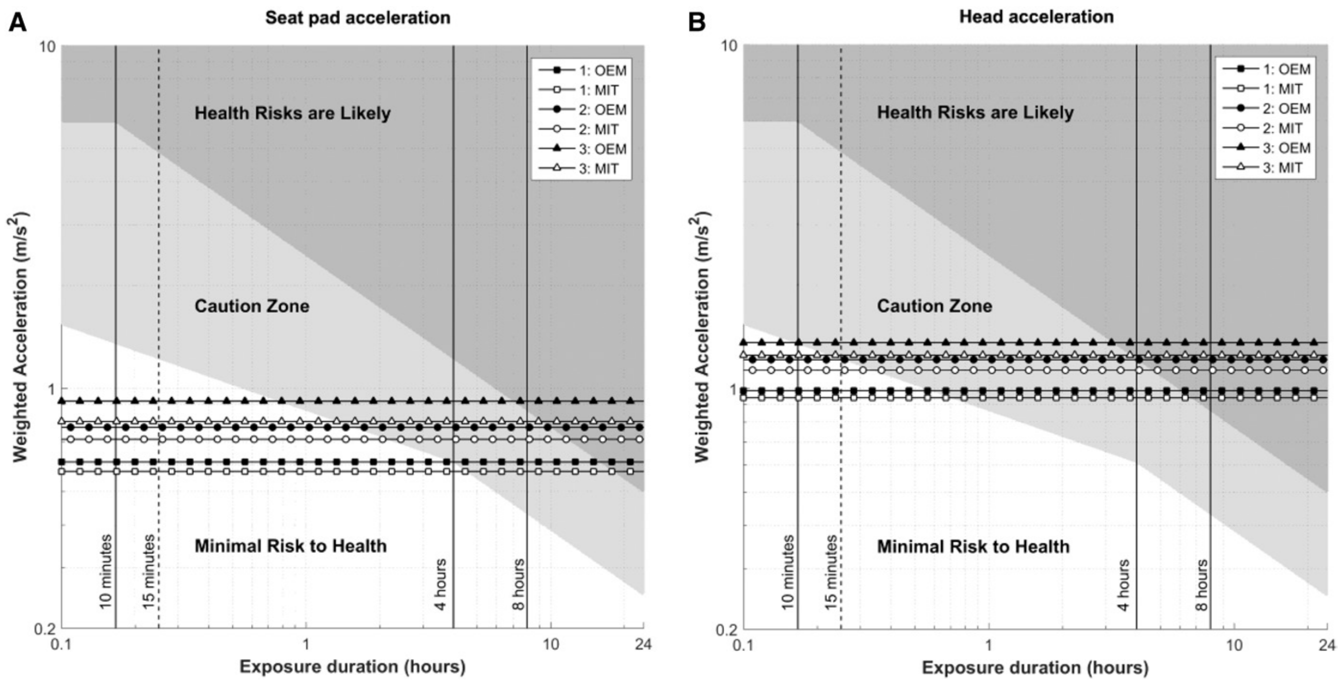

Fig. 4. ISO-2631-1-1997 Vibration Exposure Limits for seat pad (left A, current standard) and head (right B, estimated based on seat pad weightings) over the 15-min vibration exposures for the three vibration levels (1: -25%; 2: normal; and 3: +25% amplitude) when using the original standard cushion (OEM; black symbols) and vibration mitigating cushion (MIT; white symbols). The 15-min vertical dotted line represents the study duration, whereas the horizontal symbol lines represent estimations of exposure based on ISO-2631.

equipment during simulated flight missions.[15] The lateral and middle trapezius muscle fibers on the right side, and the left inferior and right superior sternocleidomastoid muscles in the current study were sensitive to the effects of cushion, potentially related to cushion thickness and posture, as measured by EMG amplitude and median frequency. In addition to the effects of vibration and cushion, an increase in the EMG amplitude and force, and a reduction in median frequency, was observed over time within each of the six vibration trials with the exception of EMG amplitude during the first vibration trial. Although this may indicate increasing levels of fatigue with vibration exposure time, further testing is required to elucidate the effects of vibration and vibration mitigating cushions over extended periods of time.

When weighted for both health and comfort according to ISO-2631-1-1997,[16] acceleration of the head (helmet) and seat pad increased with increasing vibration in the current study. Most importantly, acceleration was amplified at the head compared to the seat pad, even without considerations of added weight from equipment such as night vision goggles, head mounted displays, and/or counterweights known to increase neck loads.[13] This study focused on the physiological responses from vibration through the seat and did not take into account possible vibration transmission through the legs or arms. The current ISO standard used for WBV analysis, however, does not account for the effects of vibration on the head and neck. This is unfortunate given that neck and back pain issues have been widely reported within numerous occupations,[7] but in particular rotary wing aircrew.[1,23,24] The need to reduce WBV exposure for individuals working in vibrating environments has led to the development of various mitigation solutions, including alternate seat cushions. In the current study, the vibration MIT cushion was effective in reducing neck strain such that health-weighted head acceleration was significantly lower with the MIT cushion ($1.11 \pm 0.23\ \mathrm{m \cdot s^{-2}}$) compared to the OEM cushion ($1.19 \pm 0.26\ \mathrm{m \cdot s^{-2}}$). The MIT cushion reduced health-weighted acceleration at the head by 4.6, 6.7, and 8.0% and at the seat by 6.2, 7.7, and 12.7% for the low, normal, and high vibration levels, respectively. Given that head movement is amplified during vibration exposure, partially due to the spinal resonance of the human at around 5 Hz,[19] a reduction of this amplification with vibration mitigating technologies is ideal. The use of an active system for vibration mitigation may counter the displacement of head movement better than passive vibration mitigation (i.e., OEM cushion), however further research is required to investigate such technologies. If the head/neck were to be included in ISO-2631, revisions in the exposure limits may be required to reduce the risk of adverse health effects.

When the acceleration data was weighted for comfort according to ISO-2631-1-1997, the root-mean-square vibration level for the seat pad was within the “fairly uncomfortable” range ($0.5–1.0\ \mathrm{m \cdot s^{-2}}$) and the head was within the “uncomfortable” range ($0.8–1.6\ \mathrm{m \cdot s^{-2}}$) for all six vibration trials. The similar comfort range at the seat for all trials, due to the small differences in acceleration between trials, may in part explain the lack of significant effects of vibration level and/or cushion on the subjective measures. Although discomfort increased, and comfort decreased, with time, the change in vibration level and cushion did not have a significant impact on discomfort despite anecdotal comments from participants regarding differences in the cushions and vibration levels. The short duration of the vibration exposures (i.e., 15 min) may have contributed to a lack of significant differences. Further investigation is required to determine the most sensitive measure of subjective discomfort and optimal exposure duration for such measures relative to operational relevance. Despite the overlap between the "fairly uncomfortable" range with the "a little uncomfortable" ($0.315–0.63\ m \cdot s^{-2}$) and "uncomfortable" ($0.8–1.6\ m \cdot s^{-2}$) ranges, EMG was sufficiently sensitive to detect significant effects of vibration level and cushion despite the short duration of vibration trials. Other physiological measures and subjective ratings may require longer duration exposures to detect vibration and cushion influences. Furthermore, the health-weighted accelerations for the seat pad ranged from $\sim$0.6 to $0.9\ m \cdot s^{-2}$, which are well below the ISO 2631 caution threshold for 15-min exposures. However, using the same weighting on head acceleration places the vibration exposure within the caution range as early as 10 min at the higher vibration level, further supporting the need to re-evaluate ISO-2631-1.

Increases in EMG amplitude and decreases in median frequency with the higher vibration levels and repeated vibration exposures were indicative of increased muscle fatigue in the neck and upper back. Neck EMG was sensitive enough to detect the adverse effects of vibration level and cushion type on the human occupant, as compared to other potential indicators such as subjective ratings. Although the vibration mitigating cushion was effective in reducing the vibration transmitted to the body, acceleration levels at the head were still amplified as compared to the seat pad on which the exposure standards of ISO-2631-1-1997 are based. Thus, there is a strong justification for the inclusion of head and neck responses to WBV within the ISO-2631-1-1997 and military vibration standards and exposure limits, as there are important health and operational implications for reducing the vibration transmitted to the pilot and aircrew of rotary wing aircraft.

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REFERENCES

1. Adam J. Results of NVG-induced neck strain questionnaire study in CH-146 Griffon aircrew. Toronto, Ontario, Canada: Defence R & D Canada-Toronto, 2004; Contract No.: TR2004-153.
2. Ang B, Linder J, Harms-Ringdahl K. Neck strength and myoelectric fatigue in fighter and helicopter pilots with a history of neck pain. Aviat Space Environ Med. 2005; 76(4):375–380.
3. Balasubramanian V, Dutt A, Rai S. Analysis of muscle fatigue in helicopter pilots. Appl Ergon. 2011; 42(6):913–918.
4. Chen Y, Wickramasinghe V, Zimcik DG. Flight test of prototype seat cushion performance for helicopter aircrew whole-body vibration mitigation. Ottawa, Ontario, Canada: National Research Council Canada, 2013; Contract No.: LRT-FR-363.
5. Cifrek M, Medved V, Tonkovic S, Ostojic S. Surface EMG based muscle fatigue evaluation in biomechanics. Clin Biomech (Bristol, Avon). 2009; 24(4):327–340.
6. Craig G, Wright Beatty HE, Alexander M, Wickramasinghe V, Keillor J. Pilot head and whole body vibration response to tuning the track-and-balance of a Bell 412 main rotor. Ottawa, ON: National Research Council Canada, Aerospace, Flight Research Laboratory, 2016; Contract No.: FTR-FRL-2015-0072.
7. De Loose V, Van den Oord M, Burnotte F, Van Tiggelen D, Stevens V, et al. Individual, work-, and flight-related issues in F-16 pilots reporting neck pain. Aviat Space Environ Med. 2008; 79(8):779–783.
8. De Luca CJ. Physiology and mathematics of myoelectric signals. IEEE Trans Biomed Eng. 1979; 26(6):313–325.
9. De Luca CJ. The use of surface electromyography in biomechanics. J Appl Biomech. 1997; 13(2):135–163.
10. de Oliveira CG, Nadal J. Transmissibility of helicopter vibration in the spines of pilots in flight. Aviat Space Environ Med. 2005; 76(6): 576–580.
11. de Oliveira CG, Simpson DM, Nadal J. Lumbar back muscle activity of helicopter pilots and whole-body vibration. J Biomech. 2001; 34(10): 1309–1315.
12. Delahaye RP, Seris H, Auffret R, Jolly R, Gueffier G, Metges P. L'examen radiologique du rachis et l'aptitude b l'emploi de pilote d'helicoptere. Rev Med Aeronaut Spat. 1971;38:99–102.
13. Forde KA, Albert WJ, Harrison MF, Neary JP, Croll J. Neck loads and posture exposure of helicopter pilots during simulated day and night flights. Int J Ind Ergon. 2011; 41(2):128–135.
14. Hamberg-van Reenen HH, van der Beek AJ, Blatter BM, van der Grinten MP, van Mechelen W, Bongers PM. Does musculoskeletal discomfort at work predict future musculoskeletal pain? Ergonomics. 2008; 51(5): 637–648.
15. Harrison MF, Neary JP, Albert WJ, Veillette DW, McKenzie NP, Croll JC. Trapezius muscle metabolism measured with NIRS in helicopter pilots flying a simulator. Aviat Space Environ Med. 2007; 78(2):110–116.
16. International Organization for Standardization. Mechanical vibration and shock: evaluation of human exposure to whole-body vibration. Geneva, Switzerland: International Organization for Standardization; 1997.
17. Paddan GS, Griffin MJ. The transmission of translational seat vibration to the head–I. Vertical seat vibration. J Biomech. 1988; 21(3):191–197.
18. Phillips AS. Scope of back pain in navy helicopter pilots. [Thesis]. Monterey (CA): Naval Postgraduate School, 2011.
19. Pope MH, Wilder DG, Magnusson ML. A review of studies on seated whole body vibration and low back pain. Proc Inst Mech Eng H. 1999; 213(6):435–446.
20. Potvin JR, Brown SH. Less is more: high pass filtering, to remove up to 99% of the surface EMG signal power, improves EMG-based biceps brachii muscle force estimates. J Electromyogr Kinesiol. 2004; 14(3): 389–399.
21. Santos BR, Laviviere C, Delisle A, Plamandon A, Boileau P-E, Embeau D. A laboratory study to quantify the biomechanical responses to whole-body vibration: The influence on balance, reflex response, muscular activity and fatigue. Int J Ind Ergon. 2008; 38(7–8):626–639.
22. Seidel H, Bluethner R, Hinz B. Effects of sinusoidal whole-body vibration on the lumbar spine: the stress-strain relationship. Int Arch Occup Environ Health. 1986; 57(3):207–223.
23. Shanahan DF, Reading TE. Helicopter pilot back pain: a preliminary study. Aviat Space Environ Med. 1984; 55(2):117–121.
24. Valenti M, Prosperini V, Falzano P, Hendel M, Raimondi P. [Vibration, back pain and physical exercise in high-risk professionals: a cross-sectional study]. G Ital Med Lav Ergon. 2004; 26(3):180–182.
25. Wilder DG, Pope MH. Epidemiological and aetiological aspects of low back pain in vibration environments - an update. Clin Biomech (Bristol, Avon). 1996; 11(2):61–73.