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Evaluation of commercially available seat suspensions to reduce whole body vibration exposures in mining heavy equipment vehicle operators

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A R T I C L E I N F O

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A B S T R A C T

As mining vehicle operators are exposed to high level of Whole body vibration (WBV) for prolonged periods of time, approaches to reduce this exposure are needed for the specific types of exposures in mining. Although various engineering controls (i.e. seat suspension systems) have been developed to address WBV, there has been lack of research to systematically evaluate these systems in reducing WBV exposures in mining heavy equipment vehicle settings. Therefore, this laboratory-based study evaluated the efficacy of different combinations of fore-aft (x-axis), lateral (y-axis), and vertical (z-axis) suspensions in reducing WBV exposures. The results showed that the active vertical suspension more effectively reduced the vertical vibration (~50%; p's $<$ 0.0001) as compared to the passive vertical suspension (10%; p's $<$ 0.11). The passive fore-aft (x-axis) and lateral (y-axis) suspension systems did not attenuate the corresponding axis vibration (p's $>$ 0.06) and sometimes amplified the floor vibration, especially when the non-vertical vibration was predominant (p's $<$ 0.02). These results indicate that there is a critical need to develop more effective engineering controls including better seat suspensions to address non-vertical WBV exposures, especially because these non-vertical WBV exposures can increase risks for adverse health effects including musculoskeletal loading, discomfort, and impaired visual acuity.

1. Introduction

Heavy equipment vehicle (HEV) operators in mining industry have a high prevalence of musculoskeletal disorders (MSDs), which may be related to their high exposures to whole body vibration (WBV) (Bovenzi et al., 2006; Marin et al., 2017). Epidemiological studies have identified a positive association between exposure to WBV and risk for the development of MSDs including low back pain (LBP) and LBP-related absences (Bernard, 1997; Boshuizen et al., 1990; Bovenzi and Betta, 1994; Bovenzi et al., 2006; Howard et al., 2009; Kumar, 2004; Pope, 1991; Pope et al., 1998; Rauser et al., 2008; Rehn et al., 2002; Schwarze et al., 1998; Teschke et al., 1999; Waters et al., 2008).

As mining vehicles are operated in off-road environments, mining HEV operators' exposure is different compared to other professional on-road drivers with usually higher level of WBV exposures and especially more transient shock and impulse events adding to these vibration exposures (Fagarasanu & Kumar, 2003; Marin et al., 2017; Smets et al., 2010; Wolfgang and Burgess-Limerick, 2014). In addition, many mining equipment operators spend approximately 90% of their 12-h shifts continuously operating their equipment with limited breaks (Wolfgang and Burgess-Limerick, 2014). Furthermore, due to the rough off-road conditions, the larger wheel base, and vehicle widths, WBV in mining vehicles is often multi-axial, meaning that the amplitude of exposure in the non-vertical axes (fore-aft: x-axis and lateral: y-axis) may be of similar order of magnitude as the vertical (z) axis and perhaps even be the predominant axis (Mayton et al., 2014; Marin et al., 2017).

These different exposure patterns in mining HEVs can create different and increase risk of injury. The transient shock exposures in off-road conditions are known to contribute to the degeneration of lumbar spine more than the continuous oscillatory component (Mayton et al., 2008). Because mining vehicle operators are exposed to WBV up to 12 h (Marin et al., 2017), the prolonged exposure to multi-axial WBV can increase risks for musculoskeletal injuries through the overuse and damage to the soft tissues in the spine and associate muscles.

The multi-axial WBV exposures can increase risk for adverse health effects. Due to the substantial mass of the torso, the multi-axial WBV exposures in mining vehicles may significantly increase the biomechanical loading in the spine and associated muscles to counterbalance the inertia of the torso (Kim et al., 2018). Also, these fore-aft and lateral vibrations have been known to affect subjective discomfort, head

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acceleration, and visual acuity (Griffin and Brett, 1997; Hirose et al., 2013; Horng et al., 2015; Paddan and Griffin, 1988; Uchikune et al., 1994).

Because current industry standard seats in mining HEVs are designed to address mainly vertical vibration, the current practice may not effectively attenuate multi-axial (fore-aft and lateral) WBV exposures in mining HEVs. In addition, these suspensions may have limited WBV attenuation performance and that different suspension systems can further reduce drivers' exposure to WBV (Mayton et al., 2006; Blood et al., 2010a; Blood et al., 2010b; Kim et al., 2016a; Kim et al., 2016b; Thamsuwan et al., 2013).

Different suspension systems including multi-axial suspension have been developed for agricultural tractors and construction vehicles; however, there has been lack of systematic evaluation of the different suspension systems in reducing overall WBV exposures, especially for mining vehicle applications. As the WBV exposures can be affected by various factors including vehicle type, terrain, operator, speed, hauling weight, and task, evaluating the efficacy of different suspension systems can be done best in simulated environments where we can control and duplicate all the potential nuisance factors.

Therefore, this study evaluated different combinations of fore-aft (x-axis), lateral (y-axis), and vertical (z-axis) suspensions in order to test the efficacy of the seat suspensions to reduce WBV exposures among mining HEV operators. Our approach was to evaluate the six different combinations of fore-aft (x-axis), lateral (y-axis), and vertical (z-axis) seat suspensions in a repeated measures laboratory experimental design where a representative field-measured vibration profile were replayed onto a large-scale motion simulator with the exact same profile played for each seat suspension system tested.

2. Methods

2.1. Subjects

In a repeated-measures experimental design, eight healthy adults participated in this laboratory-based study. All the participants had driving experience (heavy equipment including semi-trucks and agricultural tractors) without current pain (past 7 days) and history of musculoskeletal disorders in the upper extremities and low back. Their average age was 38 years and ranged from 28 to 52 years. More detailed demographic information is shown in Table 1. The experimental protocol was approved by the Universities' Human Subjects Committee and all participants provided their written consent prior to their participation in the study.

2.2. Vehicle floor vibration recreation

To recreate floor vibration, we created 24 min of floor vibration profiles from data collected using tri-axial (x, y, and z) vibration profiles on the floor of 11 most commonly-used HEV during drivers' regular full shift (6–12 h) from an open-pit mine in Colombia (Marin et al., 2017). The vibration data were collected at 1000 Hz using tri-axial accelerometer (Model 356B40; PCB Piezotronics; Depew, NY) mounted on the floor of mining HEV. Marin et al. (2017) reported the details of the vibration measurement and analysis as well as the characterized WBV for these 11 vehicles using 6 and 12 h exposure metrics. We limited profiles to three vehicles: 240-ton haul truck (T240), Bulldozer, and Scraper, (chosen base on their significant operation times over 35% of total annual operating time among all vehicle types and the range of their predominant exposure axes) (Table 2). Using custom-built interactive analysis software (LabVIEW, 2016; National Instrument; TX), we parsed vibration signals from field-measured vibration profiles in our previous study such that the ISO parameters (ISO 2631-1: 1977) and exposure summary metrics of selected vibration profiles were most representative and very close to the full-shift (6–12 h) metrics calculated from the field data (Marin et al., 2017). We identified the 24-min field-measured vibration profiles collected from these three mining HEV vehicles, 8 min per vehicle (Fig. 1).

Table 1
Subject demographics.

	Age (year)	Years of driving experience (year)	Height (meter)	Weight (Kg)	Body Mass Index (BMI)
Average	38	16	1.8	81	26
SD	7.8	10.0	0.1	20.0	4.3
Range	(28–52)	(2–32)	(1.6–1.9)	(52–114)	(22–35)

Table 2
Vibration profiles from three mining HEV types (24 min total – 8 min/HEV).

Order	Description	Duration (sec)	Dominant Axis	Peak Frequency (Hz)	Percentage of total operating time per year in the mine[a]
1	T240	480	Vertical (z)	1.0–2.0 Hz	20.6%
2	Bulldozer	480	Fore/aft (x)	1.0–2.0 Hz	13.1%
3	Scraper	480	Lateral (y-axis)	1.0–2.0 Hz	1.7%

[a] Based on annual mine operation data from 2013.

To recreate these vibration profiles on a six-degree-of-freedom (6-DOF) motion platform (MB-E-6DPF, Moog Inc., East Aurora, NY), the acceleration signals had to be converted into displacement signals through a filtering process previously presented by Kim et al. (2018). The filtering process consisted of first filtering the created profile through a high pass brickwall filter: discrete Fourier transform, zero low frequency component, and then inverse discrete Fourier transform, and converted to displacement data by simple piecewise integration. The cut off frequency of the high pass filter varied from 0 to 0.5 Hz, depending on content in the road profiles. We re-filtered the vibration profile data through an iterative process until the resulting displacement was reduced sufficiently to the limits of the motion platform (Surge (x) and sway (y): ± 0.5 m; heave (z): ± 0.4 m). The differences in the average RMS amplitude between the unfiltered and the final filtered acceleration data were approximately 10%.

2.3. Seat suspensions evaluated

Three suspension systems (Seats 1 and 2: two different suspension seats + an air bladder seat cushion on Seat 2) were used for this laboratory-based study (Fig. 2).

Seat 1 was an electromagnetic active suspension seat (BoseRide; Bose Corporation; Framingham, MA). It contained an electromagnetic active suspension (vertical z-axis) and mechanical spring-based passive suspension for fore/aft (x-axis) only. The highly responsive electromagnetic active suspension system can continuously and nearly instantaneously control up-and-down (vertical) vibration induced motion. The system has a built-in microprocessor, which uses seat position and acceleration information to control the electromagnetic linear actuator. This controls the seat travel and counteracts the road-induced vibration disturbances.

Seat 2 was a passive air suspension seat (MSG 95; Grammer Seating; Hudson, WI). It has a pneumatic passive suspension (vertical z-axis) and mechanical spring-based passive suspensions for lateral (y-axis) and fore/aft (x-axis). This commercially-available seat is an industry standard for off-road vehicles such as agriculture and construction heavy equipment vehicles.

Lateral (y-axis) and fore/aft (x-axis) mechanical spring-based passive suspensions in both the electromagnetic active suspension (Seat 1) and the passive air suspension (Seat 2) can be locked (off) and unlocked

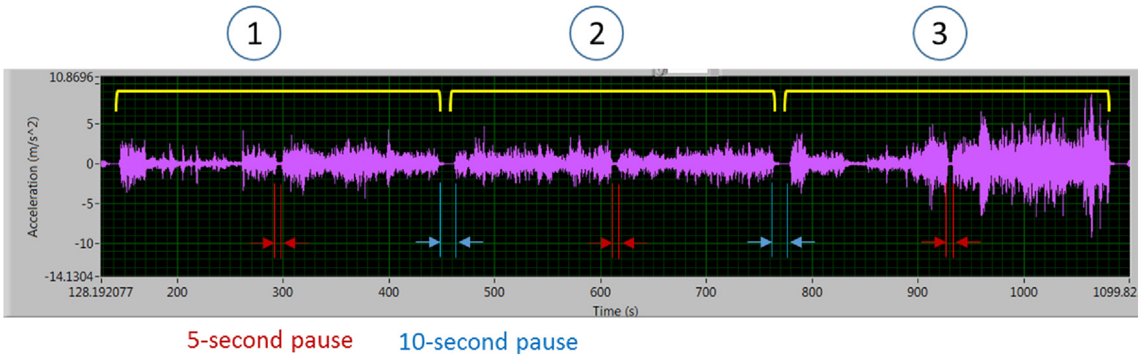

Fig. 1. Sample vibration profiles: 240-ton haul truck (1), bulldozer (2), and scraper (3). Each vehicle vibration profile is 480 s in length; there were 5-s mid-point pauses within each vibration profile (red lines and arrows) and 10-s pauses between vibration profiles (blue lines and arrows). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(on).

The integrated air-filled bladder seat cushion consisted of two air reservoirs: one on the seat back and the other on the seat pan. These two bladders were connected with three channels. When a driver is exposed to impulsive vibration, the air at the seat pan reservoir is blown out to the seat back reservoir and then instantaneously reciprocate back to the seat pan reservoir. This air bladder seat cushion is known to be effective in reducing WBV exposure up to 25% in city bus applications that also have impulsive shock exposures (Jonsson and Johnson, 2016). For this study we used the air-filled bladder on Seat 2 with the passive suspension.

2.4. Experimental design

As our aim was to systematically evaluate different seat suspensions (vertical active/passive, lateral, fore/aft suspensions, and air bladder cushion), we chose six different seat suspension combinations (Table 3) using the two commercially-available seats with and without the lateral features locked as well as the active component on and off for Seat 1 and with the air-bladder cushion on Seat 2 (Table 3).

For each condition, the same 24-min floor displacement profile created above was fed into the six-degree-of-freedom (6-DOF) motion platform (MB-E-6DPF, Moog Inc., East Aurora, NY). The 6-DOF motion platform consisted of 6 electric linear servo actuators and has been used in previous laboratory-based studies (e.g. Rahmatalla et al., 2008; Blood et al., 2015; Kim et al., 2018).

Both seats were mounted on top of the platform and two participants were tested simultaneously. For each pair of participants, each of the two would sit in one of the seats randomly assigned and the order of the three conditions were countered balanced across the eight participants. After the three conditions were tested, the two participants would change seats to complete the remaining 3 conditions.

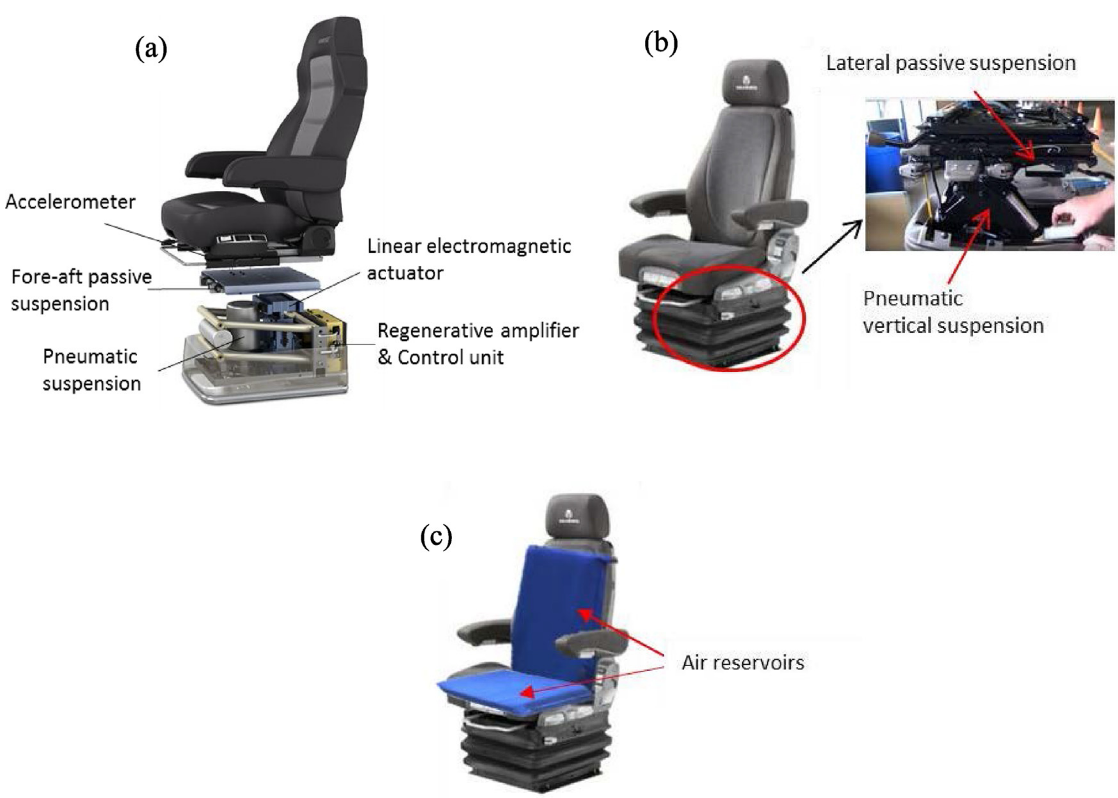

Fig. 2. Anatomy of three seating conditions: (a) electromagnetic active vertical suspension seat with fore-aft passive suspension (Seat 1: BoseRide® system); (b) Pneumatic passive vertical suspension seat with lateral passive suspension (Seat 2: Grammer MSG95 Series); (c) Air-filled bladder with two reservoirs (ErgoAir®) placed on Seat 2.

Table 3
Seat suspension combinations in the experimental design.

Condition	Seat	Vertical suspension		Fore/aft suspension	Lateral suspension	Air Cushion
		Active	Passive			
1	Seat 1 (Active)	X		X		
2		X				
3			X	X		
4	Seat 2 (Passive)		X		X	
5			X			
6			X			X

2.5. WBV exposure metrics (dependent variables)

Our primary outcomes to measure the efficacy of the suspension systems were three primary WBV exposure metrics, RMS weighted average acceleration (A_w), the vibration dose value (*VDV*), and the static spinal compression dose (S_{ed}) normalized to reflect 8 h of exposure to WBV (e.g. A (8), VDV (8), and S_{ed} (8)) (ISO 2631–1:1997 and 2631–5:2004 standards). Per International Organization for Standardization (ISO) 2631-1 WBV standards, a tri-axial seat-pad accelerometer (Model 356B40; PCB Piezotronics; Depew, NY) mounted on the seat measured WBV exposures. An identical tri-axial accelerometer magnetically mounted to the floor of the motion platform measured the floor vibrations. Raw un-weighted acceleration data were simultaneously collected on floor and seat at 1280 Hz using an eight-channel data recorder (Model DA-40; Rion Co. LTD; Tokyo, Japan).

A custom-built LabVIEW program (v2014; National Instruments; Austin, TX) calculated these WBV exposure metrics per ISO 2631-1 and 2631-5 standards (See the Appendix). These metrics were calculated for each of the three 8-min sections of the 24-min trial representing the exposure for each of the three vehicles included.

2.6. Statistical data analysis and hypothesis testing

We had five explicit hypotheses to test. They were.

1. The active suspension seat was more effective in reducing vertical WBV exposures as compared to the passive suspension seat (Condition 2 vs. 5);
2. The passive fore/aft suspension was effective in reducing WBV (Condition 1 vs. 2);
3. The passive lateral suspension was effective in reducing WBV (Condition 4 vs. 5);
4. The integrated air-filled bladder seat cushion was effective in reducing WBV (Condition 5 vs. 6); and
5. The effectiveness of passive fore/aft suspension would differ between active and passive vertical suspension systems (Condition 1 vs. 3).

As goodness-of-fit tests (*Shapiro-Wilk* test) indicated non-normality, *Wilcoxon signed-rank* tests (JMP Ver. 13 Pro, SAS Institute; Cary, SC) were used to test for differences in WBV exposures for the five stated hypotheses. Per statistical guidelines for health science journals (Altman et al., 1983), non-normal data were summarized with median and interquartile ranges. Statistical significance was noted when p-values were less than 0.05.

3. Results

The predominant axis for WBV exposures resulting from the simulated floor vibrations based on the data from three different vehicle types varied across the three 8-min profiles. (Table 4). The WBV exposure on the simulated 240-ton truck vibration was predominant on the vertical (z) axis and all the resulting WBV exposure metrics were below the EU daily action limits: A (8) = 0.5 m/s^2, VDV (8) = 9.1 m/s$^{1.75}$, and S_{ed} (8) = 0.5 MPa. For the simulated bulldozer vibration, the lateral (y) axis exposure was predominant for both A (8) and VDV (8) values which were above the action limits. Although the scrapers' WBV parameters showed that the vertical axis was predominant, the lateral (y) axis exposure values were relatively high and above the action limits. The variation across participants for the floor vibration was very small: average difference across the participants was approximately 0.4% (maximum difference: 0.7%).

3.1. Comparisons of A (8) by suspension and vehicle type

The z-axis A (8) values showed that the active vertical suspension more effectively isolated the floor vibration (~50% reduction; p's $<$ 0.005) as compared to the passive air suspension (~9% reduction; p's $<$ 0.04) and passive air suspension + air cushion (~10% reduction; p's $<$ 0.05) in all three simulated vehicle vibrations (Fig. 3). The air cushion on the passive suspension seat did not further reduce the z-axis A (8) values in all three vehicles' simulated vibration (p's $>$ 0.31). The x- and y-axis A (8) values measured on all the seats were higher as compared to the floor-measured values (p's $<$ 0.0005), indicating amplification of the vibration at the seat level. The passive fore/aft suspension seat did not effectively reduce x-axis vibration on the simulated bulldozer and scraper vibration (p's $>$ 0.13); rather, x-axis A (8) was even higher with the passive fore/aft suspension seat as compared to the seat with no lateral suspension (p = 0.03). The passive lateral suspension seat had higher y-axis A (8) values compared to the seat with no lateral suspension (p's $<$ 0.01) on the simulated scraper and bulldozer vibration, which had significant y-axial vibration. However, the y-axis A (8) values on the simulated 240-ton truck vibration did not show any difference between the seat with and without lateral suspension (p = 0.99).

3.2. Comparisons of VDV(8) by suspension and vehicle type

The z-axis VDV (8) values showed that the active vertical (z-axis) suspension seat more affectively reduced the floor-measured values on all three simulated vehicle vibrations (46–54% reduction; p's $<$ 0.0005) compared to the passive air suspension and passive air + air cushion (8–21% reduction; p's $<$ 0.11) (Fig. 4). However, no differences in the z-axis VDV (8) values were found between the passive air suspension and the passive air suspension + air cushion (p's $>$ 0.26).

For the x and y axis, the seat-measured VDV (8) values were significantly higher than the floor-measured values on all three simulated vehicle vibrations (p's $<$ 0.003). The passive fore/aft suspension did not lower the x-axis VDV (8) values on the bulldozer and scraper (p's $>$ 0.06) whereas the x-axis VDV (8) on the passive fore/aft suspension seat was lower compared to no suspension seat (p = 0.02). The y-axis VDV (8) values on the lateral suspension seat were higher than no suspension's values on the simulated bulldozer (p = 0.048) and scraper vibration (p = 0.02); however, no differences were found in the simulated 240-ton truck vibration.

Table 4
Median [1st quartile, 3rd quartile] whole body vibration parameters by six different suspension conditions for each axis.

	Vehicle	Axis	Seat 1			Seat 2		
			Active vertical + Fore/aft	Active vertical only	Passive vertical + Fore/aft	Passive vertical + lateral	Passive vertical only	Passive vertical + Air cushion
A (8) m/s^2	240-ton Truck	1.4X	0.24 [0.23, 0.25]	0.25 [0.25, 0.26]	0.24 [0.24, 0.25]	0.26 [0.25, 0.27]	0.26 [0.25, 0.27]	0.26 [0.25, 0.27]
		1.4Y	0.19 [0.18, 0.21]	0.18 [0.17, 0.20]	0.20 [0.18, 0.22]	0.16 [0.15, 0.16]	0.16 [0.16, 0.16]	0.15 [0.16, 0.17]
		Z	0.18 [0.17, 0.18]	0.18 [0.17, 0.18]	0.37 [0.35, 0.38]	0.35 [0.34, 0.35]	0.35 [0.34, 0.36]	0.34 [0.34, 0.35]
	Bulldozer	1.4X	0.37 [0.36, 0.39]	0.38 [0.37, 0.39]	0.41 [0.40, 0.41]	0.41 [0.40, 0.43]	0.41 [0.40, 0.42]	0.43 [0.41, 0.44]
		1.4Y	**0.74 [0.71, 0.81]**	**0.73 [0.67, 0.78]**	**0.75 [0.69, 0.76]**	**0.72 [0.72, 0.75]**	**0.68 [0.67, 0.69]**	**0.63 [0.61, 0.71]**
		Z	0.15 [0.14, 0.17]	0.18 [0.16, 0.19]	0.35 [0.33, 0.36]	0.34 [0.32, 0.35]	0.34 [0.33, 0.36]	0.33 [0.31, 0.37]
	Scraper	1.4X	0.43 [0.41, 0.45]	0.43 [0.41, 0.44]	0.47 [0.46, 0.51]	0.49 [0.46, 0.51]	0.50 [0.47, 0.51]	0.44 [0.42, 0.47]
		1.4Y	**0.71 [0.67, 0.80]**	**0.67 [0.63, 0.75]**	**0.75 [0.66, 0.80]**	**0.65 [0.64, 0.66]**	**0.62 [0.61, 0.63]**	**0.57 [0.54, 0.63]**
		Z	0.41 [0.39, 0.42]	0.42 [0.40, 0.42]	**0.80 [0.79, 0.84]**	**0.73 [0.69, 0.76]**	**0.74 [0.68, 0.76]**	**0.76 [0.71, 0.80]**
VDV (8) m/s^2	240-ton Truck	1.4X	5.8 [5.5, 6.0]	6.0 [5.8, 6.2]	5.4 [5.3, 5.6]	6.1 [6.0, 6.3]	6.1 [6.0, 6.3]	6.2 [6.0, 6.4]
		1.4Y	3.9 [3.6, 4.1]	3.8 [3.5, 4.1]	4.0 [3.7, 4.5]	3.2 [3.1, 3.3]	3.2 [3.2, 3.3]	3.3 [3.1, 3.4]
		Z	3.8 [3.70 3.9]	3.9 [3.7, 3.9]	7.3 [6.9, 7.4]	7.1 [6.8, 7.2]	7.1 [6.9, 7.3]	6.9 [6.8, 7.1]
	Bulldozer	1.4X	7.0 [6.8, 7.5]	7.1 [7.0, 7.4]	7.6 [7.6, 7.8]	7.6 [7.4, 7.8]	7.6 [7.4, 7.7]	8.0 [7.6, 8.2]
		1.4Y	**14.5 [14.2, 16.1]**	**14.4 [12.9, 15.1]**	**14.9 [13.9, 15.2]**	**13.8 [13.4, 14.2]**	**13.3 [13.1, 13.7]**	**12.0 [11.5, 13.7]**
		Z	3.0 [2.8, 3.3]	3.7 [3.3, 4.2]	6.4 [6.2, 6.7]	6.6 [6.3, 7.0]	6.6 [6.3, 7.1]	6.3 [6.0, 7.3]
	Scraper	1.4X	**9.5 [9.2, 9.9]**	**9.3 [8.8, 9.7]**	**10.0 [9.5, 10.8]**	**10.4 [9.8, 10.9]**	**10.4 [9.8, 10.9]**	**9.6 [9.1, 10.1]**
		1.4Y	**14.1 [13.2, 15.8]**	**13.3 [12.4, 14.7]**	**14.8 [13.0, 16.1]**	**12.4 [12.2, 12.9]**	**12.1 [11.8, 12.3]**	**11.0 [10.6, 12.2]**
		Z	**9.5 [9.3, 9.9]**	**9.6 [9.5, 9.8]**	**16.1 [15.5, 16.7]**	**15.5 [14.4, 16.0]**	**15.4 [14.1, 16.4]**	**15.9 [14.9, 18.0]**
S_{ed} (8) MPa	240-ton Truck	Σxyz	0.21 [0.19, 0.23]	0.21 [0.19, 0.22]	0.29 [0.28, 0.30]	0.24 [0.23, 0.24]	0.24 [0.23, 0.24]	0.27 [0.26, 0.28]
	Bulldozer	Σxyz	**0.60 [0.53, 0.62]**	**0.58 [0.50, 0.60]**	**0.59 [0.55, 0.65]**	0.49 [0.48, 0.51]	**0.52 [0.51, 0.53]**	0.47 [0.46, 0.51]
	Scraper	Σxyz	**0.55 [0.53, 0.63]**	**0.53 [0.50, 0.57]**	**0.75 [0.73, 0.82]**	**0.59 [0.53, 0.70]**	**0.55 [0.51, 0.68]**	**0.61 [0.55, 0.62]**

The bold numbers represent the exposure values above the European Union action limits: A (8) = 0.5 m/s^2; VDV (8) = 9.1 m/s$^{1.75}$; S_{ed} (8) = 0.5 MPa.

3.3. Comparisons of S_{ed}(8) by suspension and vehicle type

The S_{ed} (8) values on the active vertical suspension seat were lower than the floor-measured values for the simulated 240-ton truck and scraper vibration (p's < 0.02); however, the S_{ed} (8) value on the active vertical suspension seat was higher than floor-measured value for the simulated bulldozer vibration. The fore/aft (x) and lateral (y) suspension did not further reduce the floor vibration on all three simulated vehicle vibrations (p's > 0.52). The air cushion did not have any effect on the S_{ed} (8) values for the simulated bulldozer and scraper vibration (p's > 0.45) whereas the S_{ed} (8) value on the air cushion was even higher than the floor-measured values for the simulated 240-ton truck vibration.

4. Discussion

In this laboratory-base experiment where field-measured mining vehicle floor vibration profiles were reproduced using a six-degree-of-freedom motion platform, this study evaluated the efficacy of different combinations of fore-aft (x-axis), lateral (y-axis), and vertical (z-axis) seat suspensions currently commercially available in reducing WBV exposures in mining HEV operation. The results showed that the active vertical seat suspension significantly reduced the vertical (z-axis) vibration whereas passive fore-aft (x), lateral (y), and vertical (z) seat suspensions did not reduce the corresponding axial vibration; they sometimes amplified the vibration.

The results showed that the active vertical suspension more effectively reduced both the continuous oscillatory components [A (8)] and impulsive shock components [VDV (8) and S_{ed} (8)] of the floor vibration (~50%) as compared to the passive air suspension (~9%) and passive air suspension + air cushion (~10%) in all three simulated vehicle vibrations (Fig. 3). This finding is consistent with previous studies that have shown that the passive air suspension seats have limited capability to attenuate WBV (Blood et al., 2010a, 2010b, 2015; Kim et al., 2018; Thamsuwan et al., 2013). This limited attenuation performance may be because the passive air suspension has the slow response and therefore cannot react fast enough to dissipate the energy from the rapid transient exposures in rough terrain. Moreover, the results indicated that the air cushion did not reduce the vertical vibration even though a previous study showed that this air cushion reduced WBV exposure up to 25% in city bus applications (Jonsson and Johnson, 2016). This discrepancy may be explained by different dominant frequencies in vibrations between off-road mining vehicles tested in this study (Peak frequency: 1.0–2.0 Hz) and on-road buses

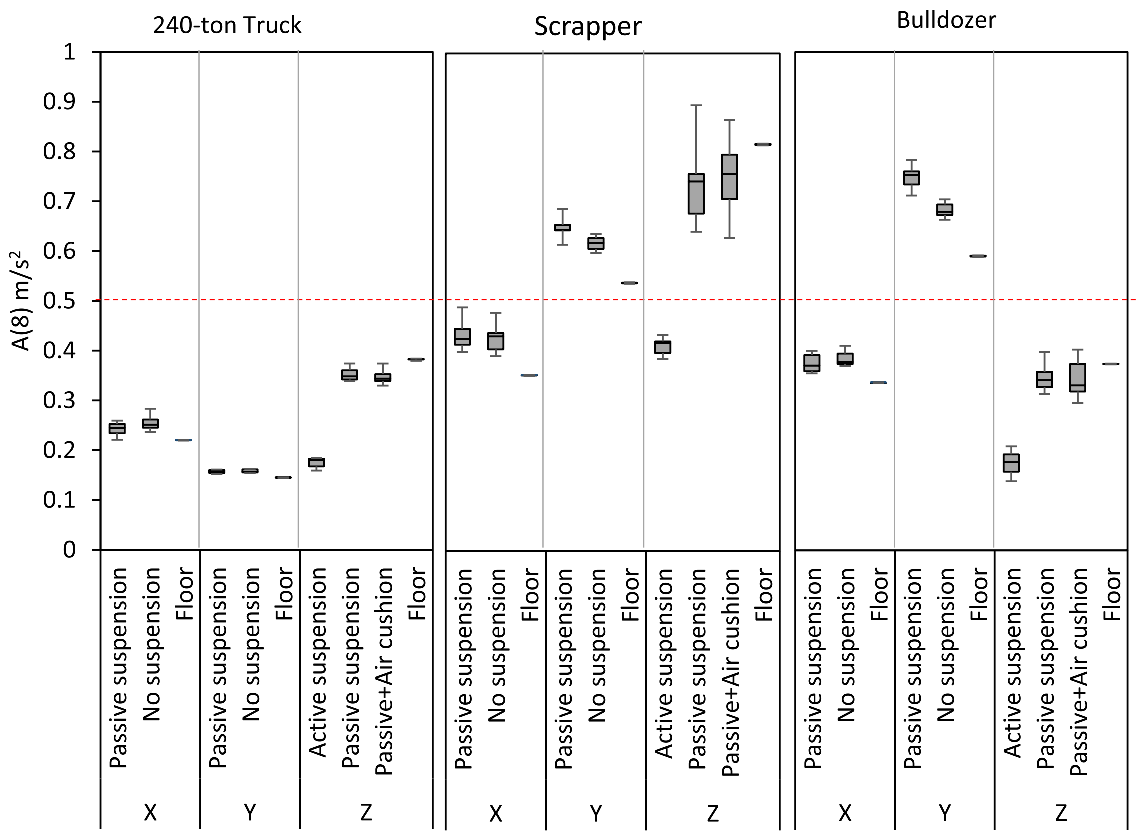

Fig. 3. Comparisons of the 8-h equivalent time-weighted average vibration [A (8)] for each seat suspension compared to the floor and for each axis grouped by vehicle type. The boxes indicate interquartile ranges; the horizontal line in the boxes are median values; and whiskers indicate maximum and minimum values. The red dotted line represents the EU daily action limits: 0.5 m/s^2. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(peak frequency: 3–16 Hz) (Blood et al., 2015). Our preliminary study (Johnson and Reynolds, 2016) showed that the air cushion was not effective in reducing relatively lower frequency vibration, which is common in off-road mining vehicles. The greater WBV reduction by the active vertical suspension indicates that the active suspension can be an effective control to reduce the vertical WBV exposure among mining vehicle operators.

The x- and y-axis vibration parameters [A (8), VDV (8) and S_{ed} (8)] measured on all the suspension conditions were not different from the corresponding floor vibration parameters or even higher especially when these non-vertical axes had significant level of WBV exposures (e.g. bulldozer and scraper). This finding indicates that the passive fore/aft (x-axis) and lateral (y-axis) suspension did not effectively reduce the corresponding axis vibration and sometimes amplified the floor vibration. Previous studies also showed that mechanical spring-based suspensions had limited attenuation performance (Blood et al., 2010a, 2010b; Kim et al., 2018). These non-vertical vibrations, especially lateral vibrations, may further elevate risks for musculoskeletal discomfort and disorders by increase muscle loads in the back and neck (Hinz et al., 2010; Kim et al., 2018), internal lumbar load (Schust et al., 2015), and head acceleration (Griffin and Brett, 1997; Hinz et al., 2010; Horng et al., 2015; Kim et al., 2018; Paddan and Griffin, 1988; Uchikune et al., 1994).

4.1. Strengths and limitations

A strength of the study was that we were able to reproduce the same floor profile across conditions and participants quite well. The variation in the floor vibration metrics was very small; due to differences in participants (e.g. weight) the variations of WBV metrics measured at the seats were a bit larger. Although this study used field-measured vibration profiles to replicate realistic off-road vehicle vibration exposures, the replicated vibration exposures in laboratory settings may be different from real field environments due to lack of the rotational acceleration. The vibration profiles used this study consisted of only translational tri-axial vibration measured from the mining HEVs' floor only (Marin et al., 2017) and did not include angular accelerations around the three axes. As a result, the complete set of accelerations and motion that participant experienced during the study may have been different than what a driver in the real field setting experiences; however, the repeated measures allowed us to compare given the same exposures across conditions. A sample of eight subjects may be considered to have been an insufficient sample size; however, given the simple study design, small standard errors and well-controlled measures, the post-hoc power analyses (JMP Ver. 13 Pro, SAS Institute; Cary, SC) indicated that this sample size would provide at least 80% of statistical power. Nonetheless, as this small same size may not be representative, the results should be carefully interpreted. Lastly, we did neither control nor measure participants' postures during the measurements. However, to have consistent postures across the experimental conditions, we asked the participants to use the backrest (leaning against it) and keep their postures similar to their regular driving postures, especially for spine angles. Therefore, despite these limitations, this study still provide useful comparative analyses in the WBV attenuation performance of various suspension combinations in mining HEV operation.

5. Conclusions

In conclusion, the findings of this study indicate that commercially-available passive suspensions for fore/aft (x), lateral (y), and vertical (z) axis have limited efficacy to reduce corresponding axis vibration

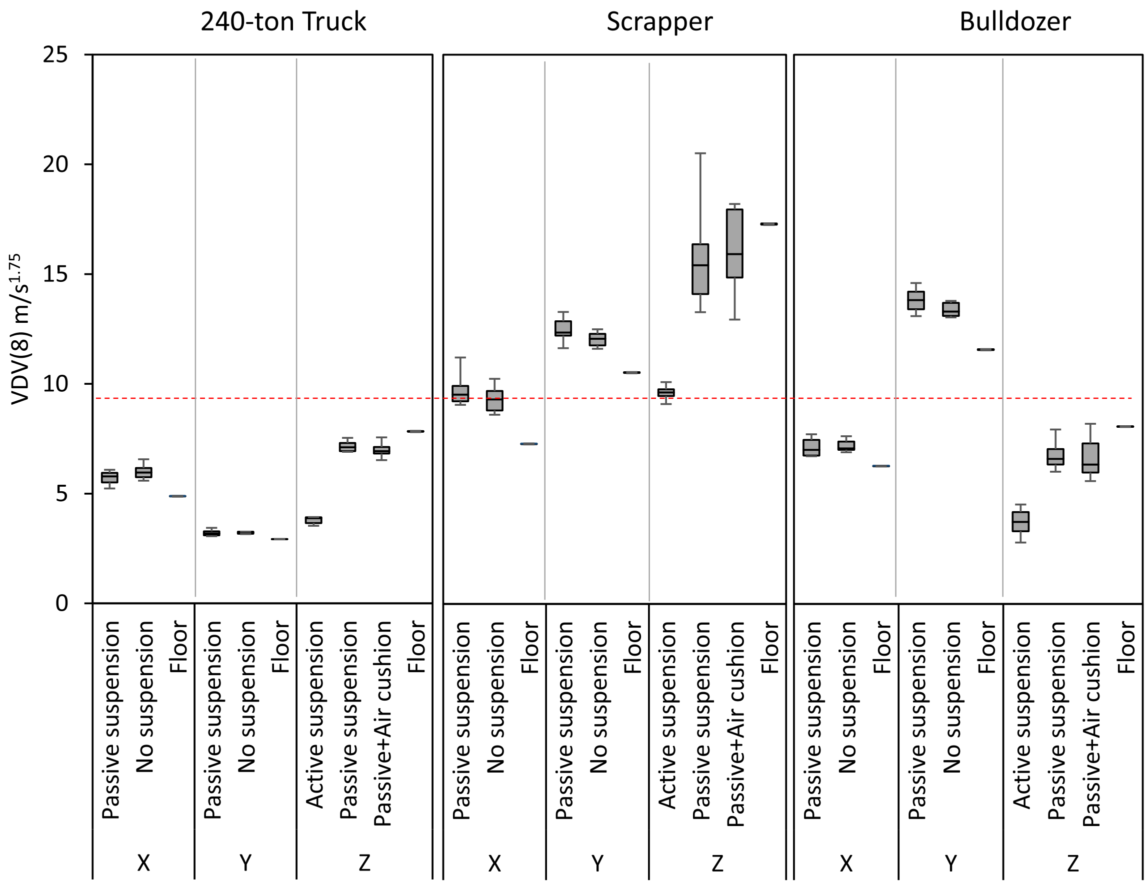

Fig. 4. Comparisons of the 8-h equivalent vibration dose value [VDV (8)] for each seat suspension compared to the floor and for each axis grouped by vehicle type. The boxes indicate interquartile ranges; the horizontal line in the boxes are median values; and whiskers indicate maximum and minimum values. The red dotted line represents the EU daily action limits: 9.1 m/s$^{1.75}$. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

whereas the vertical (z-axis) active vibration suspension system more effectively reduces the vertical vibration than the passive suspension systems. Therefore, there is a critical need to develop more effective controls to address non-vertical WBV exposures, especially given the fact that these non-vertical WBV exposures have been associated with increased biomechanical loading, subjective discomfort, head acceleration, and reduced visual acuity (Paddan and Griffin, 1988; Uchikune et al., 1994; Griffin and Brett, 1997; Hirose et al., 2013; Horng et al., 2015).

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.apergo.2018.04.003.

Appendix

A custom-built LabVIEW program (v2014; National Instruments; Austin, TX) calculated the WBV exposure parameters per ISO 2631-1 and 2631-5 standard used in this study.

ISO 2631-1 parameters

- Root mean square (r.m.s) weighted average acceleration (A_w) calculated at the seat pan, floor, and head (m/s^2):

$$A_w = \left[\frac{1}{T}\int_0^T a_w^2(t)dt\right]^{\frac{1}{2}} \tag{1}$$

where

$a_w(t)$: *instantaneous freuquency − weighted acceleration at time, t*;

T: *the duration of the measurement, in seconds.*

- Vibration dose value (VDV), which is more sensitive to impulsive vibration and reflects the total, as opposed to average vibration, over the measurement period at the seat pan and floor of the motion platform ($m/s^{1.75}$):

$$VDV = \left[\int_0^T a_w^4(t)dt\right]^{\frac{1}{4}} \tag{2}$$

ISO 2631-5 parameters

- Acceleration dose value (D_k) in m/s^2:

$$D_k = \left[\sum_{k=x,y,z} A_{ik}^6\right]^{\frac{1}{6}} \tag{3}$$

where

A_{ik}: *the* i^{th} *peak of the response acceleration* ($a_{ik}(t)$);
k: x, y, *or* z.

- Average daily dose value (D_{kd}) to which a driver will be exposed (m/s^2):

$$D_{kd} = D_k\left(\frac{t_d}{t_m}\right)^{\frac{1}{6}} \tag{4}$$

where

D_k: *acceleration dose value in equation* (3)
t_d: *the duration of the daily exposure*;
t_m: *the period over which* D_k *has been measured.*

- Daily equivalent static spinal compression dose (S_{ed}) in mega pascals (MPa):

$$S_{ed} = \left[\sum_{k=x,y,z} (m_k D_{kd})^6\right]^{\frac{1}{6}} \tag{5}$$

where

D_{kd}: *average daily dose vaule in equation in* (4)
$m_x = 0.015\ \mathrm{MPa}/(m/s^2)$
$m_y = 0.035\ \mathrm{MPa}/(m/s^2)$
$m_z = 0.032\ \mathrm{MPa}/(m/s^2)$

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