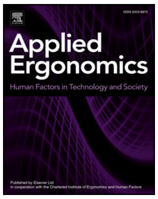
Applied Ergonomics 71 (2018) 78–86

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo



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

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ARTICLE INFO

Keywords:
Engineering control
Lateral vibration
Musculoskeletal disorders
Mining vehicles
Seat suspension
Professional drivers
Low back pain

ABSTRACT

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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https://doi.org/10.1016/j.apergo.2018.04.003
Received 22 January 2018; Received in revised form 7 April 2018; Accepted 10 April 2018

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