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Original Article

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A Randomized Controlled Trial of a Truck Seat Intervention: Part 1—Assessment of Whole Body Vibration Exposures

Peter W Johnson[1], Monica Zigman[1], Jennifer Ibbotson[1], Jack T. Dennerlein[2] and Jeong Ho Kim[3,*]

[1]Department of Environmental and Occupational Health Sciences, University of Washington, 1959 NE Pacific St, Seattle, WA 98195, USA; [2]Department of Physical Therapy, Movement and Rehabilitation Sciences, Northeastern University, 360 Huntington Ave, Boston, MA 02115, USA; [3]Environmental and Occupational Health Program, School of Biological and Population Health Sciences, Oregon State University, 20B Milam Hall, Corvallis, OR 97331, USA

*Author to whom correspondence should be addressed. E-mail: jay.kim@oregonstate.edu

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Abstract

Full-time vehicle and heavy equipment operators often have a high prevalence of musculoskeletal disorders, especially low back pain (LBP). In occupations requiring vehicles or heavy equipment operation, exposure to whole body vibration (WBV) has been consistently associated with LBP. LBP is the most common cause of work-related disability and continues to be the leading cause of morbidity and lost productivity in the US workforce. Using a parallel randomized controlled trial design, over a 12-month period, this study evaluated two different seating interventions designed to reduce WBV exposures. Forty professional truck drivers were initially recruited and randomly assigned to one of two groups: (i) a passive suspension/control group—20 drivers who received a new, industry-standard air-suspension seat, and (ii) an intervention group—20 drivers who received an active-suspension seat, which has been shown to reduce vertical WBV exposures by up to 50% compared to passive seats. WBV exposures from the truck seat and floor were collected during driver's full shifts (6–18 h) before (pre-intervention) and after the intervention (0, 3, 6, and 12 months post-intervention) per International Standards Organization (ISO) 2631-1 and 2631–5 WBV standards. After subject drop-out and turnover, 16 truck drivers remained in each group. The pre-intervention WBV data showed that there were no differences in the daily equivalent time-weighted average WBV exposures [A(8)], vibration dose values [VDV(8)], and static spinal compression doses [S_{ed}(8)] between the two groups (*P*'s > 0.36). After the new seats were installed, the A(8) values showed that the active suspension/intervention group experienced much greater reduction in the vertical (z) axis [~50%; *P* = <0.0001; Cohen's d effect size (95% CI) = 1.80 (1.12, 2.48)] exposures when compared to in the passive suspension/control group [~20%; *P* = 0.23; 0.33 (–0.36, 1.02)]. The post-intervention z-axis VDV(8) and

$S_{ed}(8)$ WBV exposure measures were not different between the two seat groups [VDV(8), $P = 0.33$; 0.35 (−0.32, 1.03); $S_{ed}(8)$, $P = 0.61$; 0.08 (−0.59, 0.76)]. These study findings indicate that, relative to the current industry-standard, passive air-suspension seats which are ubiquitous in all semi-trucks today, the active suspension seat dramatically reduced average continuous [A(8)] WBV exposures but not periodic, cumulative impulsive exposures [VDV(8) and $S_{ed}(8)$].

Keywords: long-haul truck drivers; low back pain; seat suspension; static compressive dose; vibration dose value; work-related musculoskeletal disorders

Introduction

Vehicle operators in the transportation and warehousing sector have one of the highest injury rates in the US workforce ranking third in injury and illness incidence rates and sixth in the total number of injuries and illnesses according to the United States Bureau of Labor Statistics (BLS, 2015). Previous epidemiological studies have shown that occupational exposure to whole body vibration (WBV) is associated with low back pain (LBP) (Bovenzi and Hulshof, 1999). One injury mechanism may be associated with the frequency content of the WBV exposure. When the frequency content of the vibration in the vehicle matches the natural resonant frequencies of the human spine, structures in the back are excited as a result of the WBV; therefore, the spine is thought to be exposed to greater wear-and-tear (Griffin, 1990; Thalheimer, 1996; Bovenzi, 2009; Aulck, 2012; Burström et al., 2015; Bovenzi, 2015). Impulsive, jolting and jarring WBV exposures are also thought to contribute to the wear-and-tear on the spine; and anecdotally, often the vehicle operators remember and refer to theses acute exposures as the triggering events for their LBP. The challenge for many truck drivers is that they are exposed to both continuous and impulsive WBV exposures for prolonged periods of time, which often exceeds 8 h a day and over 40 h a week.

The current ISO ISO 2631-1 WBV standard (ISO 2631-1:1997), suggests two methods for evaluating whole-body vibration exposures: (i) the weighted root mean square (r.m.s.) acceleration (A_w) in m/s^2, and (ii) when the vibration data is expected to contain mechanical shocks, the vibration dose value (VDV) in m/s$^{1.75}$. In addition, the ISO 2631-5 standard (ISO 2631-5:2004) can also be used to evaluate the vehicle operator's exposure to multiple mechanical shocks/peaks by calculating the cumulative static compressive dose (S_{ed}) in MegaPascals (MPa). The weighted root mean square vibration (A_w) was designed to measure the vehicle operator's exposure to continuous, typically lower amplitude cyclical vibration exposures. In contrast, the VDV and static compressive dose (S_{ed}) were designed to measure the cumulative impact on the vehicle operator's body from the larger amplitude mechanical shocks, jolts, and peaks.

Reducing a truck driver's exposure to the continuous and impulsive vibration may be an effective intervention for reducing LBP and other adverse health outcomes. Following the hierarchy of controls for reducing exposures in the work environment, engineering controls are often the preferred choice since they do not rely on the worker and/or management taking some sort of conscious action (Tayyari and Smith, 2003). Currently, air-suspension seats are equipped as standard equipment in most semi-trucks. These seats use passive components consisting of an air bellows and a mechanical damper which work together to attenuate WBV. With these industry-standard, passive, air-suspension seats, there sometimes is a fundamental trade-off between vibration isolation and motion. Often these air-suspension seats cannot react fast enough to dissipate the energy from large, impulse road-induced exposures. Previous studies have shown that these passive air-suspension systems have limited capability in WBV attenuation in on-road vehicles travelling at moderate to high speeds and amplify the vibration exposures in some instances, especially low frequency vibrations (Blood et al., 2010; Thamsuwan et al., 2013; Kim et al., 2016).

Recently, a new active vibration cancelling seat suspension has been developed (Blood et al., 2011). The seat uses a highly responsive electromagnetic linear actuator to continuously and nearly instantaneously control up-and-down vibration induced motion. Due to far greater fidelity in frequency response, this active suspension seat is expected to be far superior in reducing WBV compared to the conventional, industry-standard air suspension seats which are ubiquitous today. A controlled field study employing a standardized truck route has shown that this commercially available active-suspension seat reduced WBV exposures by 50% relative to the industry standard, passive, air-suspension seats (Blood et al., 2011). Therefore, using a randomized controlled trial design, the goal of this study was to conduct a field trial to determine whether there were differences in WBV exposures between two groups of truck drivers when provided with either a new, industry standard passive, air suspension seat or the new active suspension seat. The subsequent paper (Kim et al., 2018) will determine whether the introduction of either of these two seats improved any of a various array of self-reported health outcomes including LBP.

Methods

Subjects

As shown in Figure 1, our study team was able to contact 105 professional truck drivers from five different companies in the state of Washington. Among 105 truck drivers, 96 drivers expressed their willingness to participate in the study and completed an eligibility questionnaire. To be eligible to participate in the study, truck drivers had to self-report in the eligibility questionnaire that they were currently experiencing LBP (based a pain level greater than 0 evaluated using a discrete 0 to 10 point scale); spent the majority of their day driving with minimal material handling, had a minimum of 1 year employment with their current company and had no plans to retire in the next 2 years. The 1-year tenure requirement was used to minimize the chances of subject drop, driver turnover rates are much higher for new drivers (Altas Ergonomics, 2009). Based on the analysis of the eligibility questionnaires, 53 truck drivers from four trucking companies (one company chose to not participate) were eligible for this randomized controlled trial study. All the subjects were either regional or line-haul drivers, meaning they spent the majority of their day behind the wheel driving with minimum manual material handling). The experimental protocol was approved by the University's Human Subject Committee and all subjects gave their informed consent prior to their participation in the study.

Experimental design

As shown in Figure 1, from the pool of 53 eligible drivers, 40 drivers were randomly assigned into two study arms. A group of 20 drivers was assigned to the passive suspension group that received new industry-standard

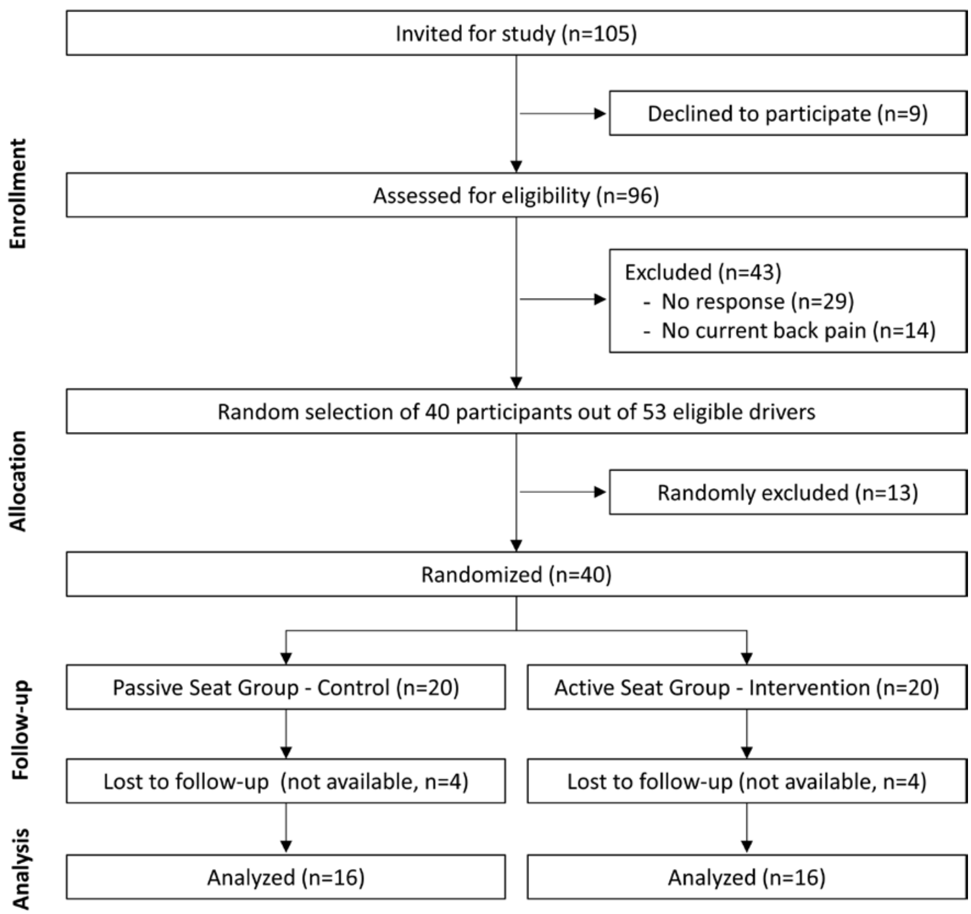

Figure 1. Study design showing the enrollment and allocation of participants to the control and intervention arms and participants lost to follow up.

air-suspension seats (National Captain Seat; Commercial Vehicle Group; New Albany, OH or Sears Elite Seat; Sears Seating; Davenport, IA). The other group of 20 drivers was assigned to the intervention group that received a new active-suspension seat (BoseRide; Bose Corporation; Framingham, MA). Then, two sets of WBV measurements were made, pre-intervention and post-intervention. Pre-intervention measurements consisted of measuring the truck drivers WBV exposures with their existing seats and the post- intervention measurements from the new seat that they received. Given the known effect of that the active suspension seat would have on WBV exposures and the variability of the exposure measures (Blood et al., 2011), a power calculations indicated that 13 subjects would have more than enough power to detect differences in z-axis A(8) WBV exposures between seats. With the known differences in WBV exposures and the financial limit of the grant funding source, 40 subjects (20 subjects per arm) were evaluated in this study. Finally, a block randomization was used to minimize any confounding that may be associated with the company (in particular differences in WBV exposures that may be associated with route differences across companies), the two seat types were randomized and roughly equally split across the pool of subjects at each company. In addition, randomization at the company level was conducted using a computer program which ran and iterative routine that minimized differences between the two pools of subjects based on truck age, truck mileage, participant age, weight, and height. After subject dropout and requiring repeated WBV measurements pre- and post-intervention 16 drivers remained in each group. A summary of the truck characteristics for each group is shown in Table 1, truck driver demographics can be found in Table 1 of the second paper (Kim et al., 2018).

Data collection and analysis

WBV

WBV data were collected at four specific time points over a 1-year study period per International Organization for Standardization (ISO) 2631-1 and 2631-5 WBV standards. A tri-axial seat-pad accelerometer (Model 356B40; PCB Piezotronics; Depew, NY) was mounted on the driver's seat; and either an identical tri-axial (Model 356B40; PCB Piezotronics; Depew, NY) or single axis (z-axis) accelerometer (Model 352C33; PCB Piezotronics; Depew, NY) was magnetically mounted to the floor of the truck cab beneath the driver's seat (Figure 2). Raw un-weighted acceleration data were collected at 1280 Hz using either a four or eight channel data recorder (Model DA-20 or DA-40; Rion Co. LTD; Tokyo, Japan) during the subjects' full work shift (8–12 h). Vehicle speed and location were simultaneously recorded at 1 Hz using a GPS logger (Model DG-100; GlobalSat; Chino, CA). Using the GPS data, we were able to specify driving and non-driving time.

As we collected full-shift WBV data, motion artifacts related to drivers' vehicle egress and ingress were expected, which could affect WBV data, especially VDV and S_{ed} values. Therefore, for these two parameters, we developed an error checking program to analyze the raw vibration only when the vehicle was moving and eliminate any potential artifacts associated with ingress and egress. Then, a custom-build LabVIEW program (v2012; National Instruments, Austin, TX) was used to process the raw unweighted data and calculate WBV exposure parameters per ISO 2631-1 and 2631-5 standards as follows:

ISO 2631-1 parameters

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

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

where

$a_w(t)$: *instantaneous frequency – weighted acceleration at time, t;*
T: *the duration of the measurement, in seconds.*

- 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 trucks (m/s$^{1.75}$):

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

Table 1. Mean (SE) truck characteristics for each seat group.

Group	Trucks	
	Age (years)	Mileage (10^6 km)
Passive suspension (n = 20)	8.3	1.1
	(1.5)	(0.2)
Active suspension (n = 20)	7.6	0.9
	(1.3)	(0.1)
P-value	0.37	0.42

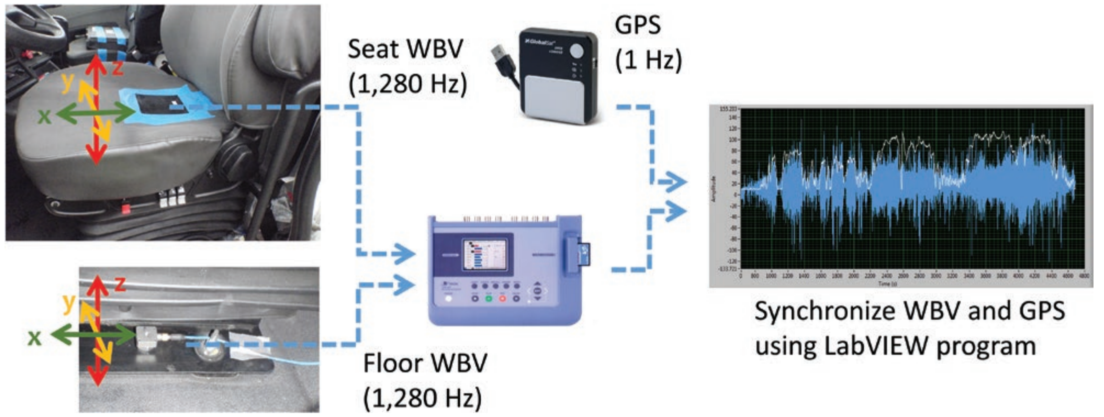

Figure 2. Data acquisition system. Tri-axial accelerometer axes: fore-aft (x), lateral (y) and vertical (z).

ISO 2631-5 parameters

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

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

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 truck driver will be exposed (m/s^2):

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

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}):

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

where

D_{kd} : *average daily dose value in equation in* (4)
$m_x = 0.015\,\text{MPa} / (m/s^2)$

$$m_y = 0.035\,\text{MPa} / (m/s^2)$$

$$m_z = 0.032\,\text{MPa} / (m/s^2)$$

To enable comparisons across all measurements, all the parameters (A_w, VDV, S_{ed}) were normalized to reflect 8 h of driving exposure (e.g. $A(8), VDV(8)$, and $S_{ed}(8)$). The daily vibration values reflected the exposure as if each driver operated their vehicle for 8 h a day. The vector sum (Σ) WBV exposures measured at the seat were also calculated as follows:

$$\sum A(8) = \left[\sum_{i=x,y,z} \left(k_i A(8)_i \right)^2 \right]^{\frac{1}{2}};$$

$$\sum VDV(8) = \left[\sum_{i=x,y,z} \left(k_i VDV(8)_i \right)^4 \right]^{\frac{1}{4}};$$

$$k_i = \begin{cases} 1.4 & i = x, y \\ 1 & i = z \end{cases}$$

Due to different standard and regulations nomenclature, to assess the WBV exposures across the various WBV standards (ISO 2631-1, ISO 2631-5) and European Union (EU) regulations (European-Council, 2002), the following terminology was adopted. Above daily exposure action limits was used to refer to: (i) A(8) values above 0.5 m/s^2, the lower limit of the ISO 2631-1 health caution guidance zone and the daily exposure action values in the EU vibration directive; (ii) VDV(8) values above 9.1 m/s$^{1.75}$, the lower limit of the ISO 2631-1 health caution guidance zone and the daily exposure action values in the EU vibration directive; and (iii) $S_{ed}(8)$ values above 0.5 MPa, the lower limit of the ISO 2631-5 standard where the probability of adverse health outcomes is thought to increase.

Finally, as shown in equation (7), the z-axis Seat Effective Amplitude Transmissibility (SEAT) values were calculated for $A(8)$ and $VDV(8)$ to determine how well the seats attenuated the vibration measured at the truck floor. Since seat attenuation performance should be based on when the truck is moving, the GPS data was used to identify all the data where the trucks were in motion (defined as faster than 5 km/hour) and the SEAT(%) values were calculated from the data when the truck was moving.

$$SEAT(\%) = \frac{parameter\ value_{seat}}{parameter\ value_{floor}} \times 100 \qquad (7)$$

Statistical analysis

As WBV data were not normally distributed with missing values, *Skillings.Mack* (generalized *Friedman*) tests in R (R 3.2.4; R Development Core Team) were used to determine whether the new active suspension seat had better WBV attenuation performance than conventional passive air suspension seats. *Wilcoxon tests* were used to compare the pre-intervention WBV measures between the intervention and passive suspension groups. Non-normal WBV data were summarized with median and interquartile range (25th–75th percentile) per a recommendation by Altman et al. (1983). Statistical significance was noted when *P*-values were less than 0.05. When important *P*-values were reported in the text, effect sizes and their 95% confidence intervals (CI) were also calculated using *Cohen's d*. In our application, *Cohen's d* was calculated taking the difference between the two means of interest and dividing by the pooled standard deviation from the appropriate statistical test. Cohen's d yields a standardized value where the effect size is expressed in units of standard deviation. A *Cohen's d* of 0.20 or less indicates small to negligible differences/changes, values near 0.50 indicate moderate differences/changes and values greater than 0.80 indicate large differences/changes.

Results

The full-shift (6–18 h) acceleration data were analyzed to characterize the truck drivers' WBV exposures. Based on the GPS data, during the full shift, driving and non-driving times (mean ± SD) were 7.0 ± 2.5 and 4.7 ± 3.0 h, respectively. We included both driving and non-driving hours in the A(8) WBV analysis to reflect the realistic exposure pattern (exposure duty cycle). However, the impulsive WBV exposure measures VDV(8) and Sed(8) were based solely on the driving exposure to eliminate known impulsive artifacts associated with drivers getting in and out of their truck seats. As Tables 2–4 demonstrate, based on the floor-measured vibration values the vertical (up-and-down) z-axis was the predominant axis of exposure for all the exposures (A(8), VDV(8), $S_{ed}(8)$). In addition, floor-measured WBV exposures across all three axes did not change pre- and post-intervention (Tables 2–4), indicating that floor-measured WBV exposures were similar for both seat groups and pre- and post-intervention.

The A(8) average daily weighted WBV exposures by axis and vector sum (Σ) are summarized in Table 2. The pre-intervention predominant, z-axis A(8) WBV exposures in both groups were below the ISO daily action limit (0.5 m/s²); however, the vector-sum A(8) WBV exposures in both groups exceeded the ISO daily action limit. Importantly, from an intervention standpoint there was no difference in the pre-intervention WBV exposure between the two groups, at both the floor and seat. In addition, floor-measured A(8) WBV exposures did not change post-intervention (Table 2). As a result, the floor-measured WBV exposures were similar for both seat groups.

With respect to the seat-measured exposures, only the z-axis A(8) exposures changed post-intervention;

Table 2. Median (25th %tile, 75th %tile) single axis and vector sum (Σ) A(8) average daily weighted vibration WBV exposures by seat group, pre- and post-intervention. *P*-values in the right side of the table compare the pre- and post-intervention measures between the two seat groups.

		Passive			Active			Passive versus active p-value	
		Pre (n = 20)	Post (n = 16)	*P*-value	Pre (n = 20)	Post (n = 16)	*P*-value	Pre	Post
Seat	1.4X	0.22 (0.20,0.30)	0.23 (0.21,0.30)	0.91	0.24 (0.21,0.30)	0.24 (0.21,0.27)	0.85	0.80	0.92
	1.4Y	0.23 (0.22,0.38)	0.25 (0.22,0.28)	0.70	0.29 (0.21,0.37)	0.24 (0.20,0.28)	0.13	0.68	0.63
	Z	0.42 (0.28,0.52)	0.33 (0.27,0.41)	0.23	0.41 (0.26,0.47)	0.22 (0.19,0.25)	<0.0001	0.50	0.0006
	Σ	0.55 (0.44,0.74)	0.51 (0.43,0.58)	0.38	0.58 (0.48,0.63)	0.42 (0.38,0.46)	0.001	0.73	0.007
Floor	1.4X	0.15 (0.14,0.18)	0.17 (0.16,0.23)	0.19	0.16 (0.14,0.20)	0.17 (0.16,0.19)	0.37	0.95	0.56
	1.4Y	0.16 (0.13,0.19)	0.18 (0.14,0.25)	0.28	0.17 (0.13,0.20)	0.16 (0.14,0.18)	0.72	0.69	0.17
	Z	0.38 (0.34,0.42)	0.37 (0.34,0.43)	0.75	0.38 (0.29,0.41)	0.39 (0.32,0.46)	0.51	0.50	0.51
	Σ	0.40 (0.37,0.46)	0.46 (0.41,0.56)	0.09	0.41 (0.35,0.55)	0.46 (0.39,0.53)	0.47	0.89	0.81

Table 3. Median (25th %tile, 75th %tile) single axis and vector sum (Σ) VDV(8) impulsive WBV exposures by seat group, pre- and post-intervention. *P*-values in the right side of the table compare the pre- and post-intervention measures between the two seat groups.

		Passive			Active			Passive versus active *P*-value	
		Pre (n = 20)	Post (n = 16)	*P*-value	Pre (n = 20)	Post (n = 16)	*P*-value	Pre	Post
Seat	1.4X	7.1 (6.2,17.9)	7.7 (6.7,9.7)	0.88	8.4 (6.5,13.0)	7.4 (6.1,9.9)	0.49	0.93	0.53
	1.4Y	7.5 (6.6,14.8)	7.1 (6.5,11.7)	0.35	9.9 (7.2,16.1)	6.5 (5.7,8.8)	0.04	0.70	0.30
	Z	10.0 (7.1,11.9)	8.6 (8.2,10.5)	0.56	10.0 (7.2,11.5)	8.4 (6.9,9.6)	0.18	0.83	0.33
	Σ	11.2 (9.4,24.7)	11.9 (10.4,14.9)	1.00	12.7 (11.1,17.4)	10.6 (9.2,14.5)	0.10	0.91	0.34
Floor	1.4X	4.8 (4.1,6.6)	5.8 (4.5,10.4)	0.38	5.0 (4.2,9.9)	5.2 (4.3,6.6)	1.00	0.86	0.53
	1.4Y	4.5 (4.2,11.3)	4.5 (4.3,13.5)	0.88	4.9 (4.1,11.4)	4.7 (4.0,6.1)	0.42	0.95	0.40
	Z	9.9 (9.2,10.9)	9.9 (9.1,11.7)	0.86	9.7 (8.9,11.0)	9.9 (9.2,11.7)	0.78	0.93	0.97
	Σ	10.2 (9.1,13.1)	11.5 (9.5,18.9)	0.68	10.9 (8.6,12.9)	10.1 (9.5,12.3)	0.86	0.89	0.56

Table 4. Median (25th %tile, 75th %tile) single axis and vector sum (Σ) Sed(8) impulsive WBV exposures by seat group, pre- and post-intervention. *P*-values in the right side of the table compare the pre- and post-intervention measures between the two seat groups.

		Passive			Active			Passive versus active *P*-value	
		Pre (n = 20)	Post (n = 16)	*P*-value	Pre (n = 20)	Post (n = 16)	*P*-value	Pre	Post
Seat	X	0.15 (0.14,0.25)	0.16 (0.13,0.19)	0.86	0.17 (0.13,0.22)	0.15 (0.13,0.21)	0.55	0.96	0.75
	Y	0.37 (0.33,0.5)	0.33 (0.28,0.44)	0.28	0.38 (0.28,0.55)	0.31 (0.27,0.53)	0.51	0.70	0.95
	Z	0.42 (0.28,0.81)	0.39 (0.33,0.55)	0.99	0.43 (0.31,0.56)	0.40 (0.33,0.71)	0.90	0.75	0.61
	Σ	0.49 (0.37,0.84)	0.54 (0.39,0.63)	0.86	0.49 (0.4,0.69)	0.47 (0.38,0.82)	0.63	0.54	0.87
Floor	X	0.11 (0.08,0.17)	0.11 (0.08,0.18)	0.76	0.10 (0.08,0.17)	0.12 (0.08,0.17)	0.64	0.86	0.81
	Y	0.34 (0.23,0.45)	0.21 (0.18,0.54)	0.32	0.20 (0.17,0.30)	0.25 (0.17,0.35)	0.58	0.11	0.78
	Z	0.31 (0.27,0.4)	0.32 (0.28,0.37)	0.68	0.38 (0.29,0.47)	0.31 (0.27,0.38)	0.13	0.17	0.68
	Σ	0.33 (0.3,0.54)	0.38 (0.27,0.62)	1.00	0.45 (0.27,0.58)	0.39 (0.30,0.47)	0.52	0.41	0.98

and there were exposure reductions with both seats (Table 2). In addition, post-intervention, the active suspension seat group had z-axis A(8) WBV exposures that were 0.11 m/s^2 or 50% lower [P = 0.0006; Cohen's d effect size (95% CI) = 1.17 (0.49, 1.85)] compared to the passive suspension seat group (Table 2). With respect to the seat-measured vector sum A(8) exposures, only the post-intervention measures in the active suspension seat group were below the ISO daily action limit values (0.50 m/s^2).

Table 3 summarizes daily vibration dose value VDV(8) WBV exposures. The VDV is a cumulative measure characterizing the impulsive exposures over the course of an 8 h per day. Unlike the A(8) exposures, the pre-intervention seat-measured VDV(8) exposures were all above the ISO daily action limit values (9.1 m/s$^{1.75}$). Pre-intervention, at both the floor and seat, there were no differences in VDV(8) exposures between the two seat groups (Table 3). In addition, the floor-measured VDV(8) exposures did not change between pre and post-intervention. Finally, there were no meaningful VDV(8) exposure reductions with either type of seat.

Daily equivalent static spinal compression dose, S_{ed}(8), is summarized in Table 4. The pre-intervention floor-measured S_{ed}(8) values were not different between the intervention and passive suspension groups [P = 0.17; 0.48 (−0.21, 1.18)] nor were there any changes in the floor-measured exposures pre- and post-intervention.

The pre-intervention seat-measured S_{ed}(8) exposures were not different between the active and passive suspension groups [P = 0.75; 0.16 (−0.53, 0.85)]. These pre-intervention seat-measured S_{ed}(8) values in both treatment groups were just below the ISO daily action limit (0.5 MPa). Post-intervention, the were no changes in S_{ed}(8) exposures in either group.

Table 5. Median (25th %tile, 75th %tile) z-axis SEAT values by seat, pre- and post-intervention. *P*-values in the right side of the table compare the pre- and post-intervention measures between the two seat groups.

	Passive			Active			Passive versus active *P*-value	
	Pre (n = 20)	Post (n = 16)	*P*-value	Pre (n = 20)	Post (n = 16)	*P*-value	Pre	Post
A(8)	0.93 (0.73,1.09)	0.78 (0.69,0.89)	0.08	0.90 (0.80,1.00)	0.49 (0.39,0.71)	0.0001	0.46	0.001
VDV(8)	0.97 (0.79,1.08)	0.89 (0.74,1.02)	0.54	0.95 (0.86,1.04)	0.77 (0.71,1.00)	0.09	0.83	0.31
Sed(8)	1.38 (0.97,1.76)	1.21 (0.8,1.44)	0.61	1.19 (0.91,1.61)	1.24 (1.08,2.01)	0.23	0.77	0.43

As shown in Table 5, by comparing the ratio of the pre-intervention z-axis seat- and floor-measured vibration (SEAT), the seats in both groups of drivers slightly attenuated (5–10%) the A(8) vibration exposures. Post-intervention, based on the SEAT ratios, the new air-suspension seats in the passive suspension group reduced z-axis A(8) WBV exposures by 15% [P = 0.08; 0.25 (–0.44, 0.94)] and the active-suspension seats in the intervention group reduced the z-axis A(8) exposures by 41% [P = 0.0001; 1.47 (0.79, 2.14)]. By comparing the z-axis VDV(8) SEAT ratios, the seats in both groups of drivers slightly attenuated (3–5%) the floor-measured WBV exposures pre-intervention. Post-intervention, the new air-suspension seats in the passive suspension group reduced z-axis VDV(8) SEAT ratios by 8% [P = 0.54; 0.15 (–0.54, 0.84)] and the active suspension seats reduced the SEAT ratios by 18% [P = 0.09; 0.43 (–0.25, 1.10)]. Finally, both pre- and post-intervention, both seats amplified the raw-impulsive $S_{ed}(8)$ exposures.

Discussion

This randomized controlled trial, using two groups of truck drivers, evaluated a new engineering control (an active suspension seat) to determine whether there would be WBV exposure differences in comparison to an industry-standard, passive air-suspension seat. The results showed that there were no differences in the x- and y-axis WBV exposures between the two seats; however, there were parameter dependent z-axis exposure differences between seats. Also of importance, based on the floor-measured WBV exposures, was that there were no differences in floor-measured exposures between groups. The floor-measured vibration exposures were the same for the two seating groups both pre- and post-intervention. In addition, within each seat group, the floor-measured vibration did not change pre- and post-intervention, indicating the WBV exposures did not change over time.

The WBV exposure parameter dependence in the z-axis showed that the with both seats the greatest reductions were seen in the continuous weighted-average WBV exposures [A(8)]; to a lesser degree, with the time-weighted average impulsive measures [VDV(8)]; and to a very limited degree in the raw, impulsive exposure measures [$S_{ed}(8)$]. This appears to indicate that truck seats may have a greater effect on reducing average continuous WBV exposure [A(8)] and minimal to no effects on impulsive WBV exposure parameters [VDV(8) and $S_{ed}(8)$].

With respect to the seat-related performance differences, the reduction in z-axis seat-measured WBV exposures were greatest in the group of truck drivers that received the active suspension seats. As shown in the z-axis, A(8) seat measures in Table 2, post-intervention results showed that the active suspension seat group experienced almost a 50% reduction [P < 0.0001; Cohen's d effect size (95% CI) = 1.80 (1.12, 2.48)] while the passive suspension group had 21% reduction in A(8) exposures [P = 0.23; 0.33 (–1.02, 0.36)]. The 50% or 0.11 m/s^2 additional reduction in the active suspension group compared to the passive suspension group [Table 2, P = 0.0006; 1.17 (0.49, 1.85)] indicates that the active suspension seat was much more effective in reducing continuous weighted-average vibration as compared to the passive suspension. However, the post-intervention changes in the z-axis, seat-measured impulsive WBV exposure measures (Tables 3 and 4) were not different between seats [VDV(8), P = 0.31;0.33 (–0.35, 1.01); $S_{ed}(8)$, P = 0.43; 0.11 (–0.56, 0.79)].

The pre-intervention, z-axis A(8) Seat Effective Amplitude Transmissibility (SEAT) values showed that there were no difference between groups [P = 0.46; 0.14 (–0.55, 0.83)] and that the existing seats transmitted around 90% of the floor-measured vibration to the truck operator. Previous studies also have shown that the current industry-standard, passive air suspension seats have limited WBV attenuation performance in metro buses and long-haul trucks (Thamsuwan et al., 2013; Kim et al., 2016). This may be due to the slow response of these air-suspension seats to road perturbations, especially when going at moderate to high speeds. .The differences between seats indicate that the air-suspension seats cannot react fast enough to dissipate the A(8) vibration energy created or transmitted by the truck floor. In addition, the VDV(8) and $S_{ed}(8)$ SEAT ratios show that both seats slightly attenuated the time-weighted impulsive VDV(8) exposures and amplified the raw-impulsive $S_{ed}(8)$ exposures. The more impulsive the exposures, the poorer both seats performed. The greater A(8) WBV reduction by the active suspension indicates that seat interventions can be an effective engineering control to reduce the exposure to occupational WBV among truck drivers. In addition, the passive seat's 15% reduction [P = 0.09; 0.43 (−0.25, 1.10)], of the post-intervention A(8) SEAT values demonstrates that a periodic passive seat replacement may also be a potential administrative control to reduce a truck driver's exposure to WBV.

Finally, the pre-intervention seat-measured z-axis A(8) values in both groups were below the ISO daily action limit (0.50 m/s^2) whereas the pre-intervention seat-measured VDV(8) and $S_{ed}(8)$ values in both groups were at or above action limits (9.1 $m/s^{1.75}$ and 0.50 MPa, respectively). This indicates that the long-haul truck drivers evaluated in this study, and more generally, in North America (due to the truck cab design where the truck cab is suspended between the front and rear axles), may be exposed to a high level of impulsive exposures and no seats currently work well at reducing impulsive exposures. Previous studies have also shown that impulsive exposures are more prominent and limiting factors in driving time (Kim et al., 2016).

Strengths and limitations

This study has many strengths in terms of study design as this is the first randomized controlled trial (RCT) study to systematically and prospectively evaluate new seat suspension technologies as an engineering control to reduce WBV exposures and associated health outcomes (presented in the subsequent paper, Kim et al., 2018;). Furthermore, although this study had a relatively small sample size (n = 20 per study arm) for a randomized control trial, our power calculation based on our previous studies (Blood et al., 2011) showed that this sample size will provide at least 80% of statistical power to detect the differences in WBV exposures between the active and passive suspension group. However, this study does have some limitations. For example, as a longitudinal study, this study did suffer from some subject drop out; this is in part because trucking industries have been experiencing very high turnover rate over the past few decades (Costello and Suarez, 2015). In addition, due to grant funding, we were limited on the number of subjects we could evaluate (n = 20 per group, 40 total) and the study would have benefited from a larger sample size which would have increased the statistical power.

Conclusions

This study was conducted to determine whether there were WBV exposure differences between an industry standard passive suspension seat and a newly-developed active suspension seat. The long-term goal of this work was to determine whether either type of seat may improve truck drivers' LBP and other health outcomes (see the subsequent paper, Kim et al., 2018). There were no differences in x- and y-axis WBV exposures between the two seats; however, there were differences between seats in the predominant z-axis WBV exposures and the magnitude of those differences were parameter dependent. The study results demonstrated that the intervention (active suspension) truck seat substantially reduced the z-axis continuous weighted average WBV exposures [A(8)] compared to passive air suspension seat; however, there were no differences between seats in the impulsive WBV exposures [VDV(8) and $S_{ed}(8)$]. Therefore, the study findings indicate that active suspension seat was a more effective engineering control for reducing truck drivers' exposure to the continuous, average cyclical vibrations compared to the periodic, impulsive vibration exposures. In the future, it could be beneficial if both active and passive suspension seats could also be designed to better mitigate the impulsive exposures.

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Conflict of Interest

The authors declare no conflict of interest.

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