



# Whole Body Vibration Exposures and Health Status among Professional Truck Drivers: A Cross-sectional Analysis

Jeong Ho Kim<sup>1\*</sup>, Monica Zigman<sup>2</sup>, Lovenoor S. Aulck<sup>2</sup>, Jennifer A. Ibbotson<sup>2</sup>, Jack T. Dennerlein<sup>3</sup> and Peter W. Johnson<sup>2</sup>

1.Environmental and Occupational Health Program, Oregon State University, Corvallis, OR, USA;

2.Department of Environmental and Occupational Health Sciences, University of Washington, Seattle, WA, USA;

3.Department of Physical Therapy, Movement and Rehabilitation Sciences, Northeastern University, Boston, MA, USA

\*Author to whom correspondence should be addressed. Tel: +1-541-737-2166; e-mail: [jay.kim@oregonstate.edu](mailto:jay.kim@oregonstate.edu)

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## ABSTRACT

Many professional truck drivers suffer from low back pain (LBP) which is thought to be associated with exposure to whole-body vibration (WBV). The objectives of this study were to: (i) characterize general health, regional body pain and WBV exposures, (ii) evaluate the associations between different WBV parameters and health outcomes, and (iii) determine whether there were factors which affect a truck driver's WBV exposures. This study analyzed WBV exposures from 96 long-haul truck drivers over their regular work shift (6–15 h) per International Standards Organization (ISO) 2631-1 and 2631-5 WBV standards. This study also evaluated regional body pain (10-point scale), low back disability (the Oswestry Disability Index), and physical and mental health (the Short Form 12-item Health Survey). The results demonstrated that the daily vector sum WBV exposures [ $A(8)$ ,  $VDV(8)$  and  $S_{ed}(8)$ ] were above action limits while the predominant z-axis exposures were below action limits. Among all the musculoskeletal outcomes, LBP was the most prevalent (72.5%) with average LBP score of 2.9 (SD: 2.0). The SF-12 health scores demonstrated that truck drivers in general had lower physical health status than the general US population ( $P$ 's < 0.04) and that physical health status decreased as WBV exposures increased ( $P = 0.03$ ). In addition, the correlations between the WBV measures and health outcomes indicated that  $A(8)$  exposure measures had a stronger link to musculoskeletal (LBP) and other health outcomes than the  $VDV(8)$  and  $S_{ed}(8)$  measures. Finally, seat manufacturer and seat age were two factors which had a strong influence on WBV exposures.

**KEYWORDS:** human vibration; low back pain; Oswestry disability index; SF-12 health survey; work-related musculoskeletal disorders

## INTRODUCTION

Work-related musculoskeletal disorders (WMSDs) have been the single largest component of nonfatal occupational injuries and illnesses (Punnett and

Wegman, 2004; Rauser *et al.*, 2008; BLS, 2014). Among WMSDs, low back pain (LBP) is the most common worker's compensation claim (Punnett *et al.*, 2005; Rauser *et al.*, 2008). LBP is also the most

common cause of persistent disability claims and continues to be the leading cause of morbidity and lost productivity in the workplace (Ammendolia *et al.*, 2009). Worker disability can significantly increase the economic burden on employers due to worker's compensation claims and lost productivity. Moreover, there are costs to the injured worker as well including a reduced quality of life and often reduced or lost wages. Punnett *et al.* (2005) estimated that worldwide work-related LBP may result in ~818 000 disability-adjusted lost life years annually.

Previous epidemiological studies have shown that whole body vibration (WBV) has a strong association with occupational LBP in professional vehicle operators (Pope, 1991; Bovenzi and Betta, 1994; Bovenzi, 1996, 2009; Bernard, 1997; Bovenzi and Hulshof, 1999). Some experimental studies demonstrated that exposure to the WBV may result in elevated spinal load (Fritz, 1997, 2000), muscle fatigue (Wilder *et al.*, 1996), and the deterioration of intervertebral discs (Griffin, 1990; Thalheimer, 1996). Furthermore, WBV can adversely affect musculoskeletal, cardiovascular, cardiopulmonary, metabolic, endocrinologic, nervous and the gastrointestinal systems of the body (Gruber and Ziperman, 1992; Thalheimer, 1996). Among all the occupational injuries, LBP appears to be the most common and costly component.

Long-haul truck drivers in North America are exposed to continuous WBV for prolonged periods of time, up to 13 h a day and 80 h a week (Canadian Justice, 2009). This prolonged exposure to WBV likely contributes to their numerous health issues and higher prevalence and injury rates. As a result, professional truck drivers rank second among all the occupations in number of non-fatal occupational illnesses (BLS, 2014), have an illnesses and injuries incidence rate over three times higher and a median duration away from work twice as long when compared to workers in other industries (Rauser *et al.*, 2008).

To reduce WBV exposure, previous studies have investigated various factors affecting WBV exposure in different vehicles including buses, forklifts, and small trucks (Makhous *et al.*, 2005; Blood *et al.*, 2010, 2011; Motmans, 2012; Thamsuwan *et al.*, 2013). These studies have shown that vehicle design, road surface, speed, and seat suspension and design have an influence on WBV exposures. However, there has been a lack of studies on factors affecting WBV exposure in

truck drivers in actual field settings. Therefore, the aims of this study were to characterize general health, regional body pain and WBV exposures in a group of truck drivers, determine whether there were differences between the WBV exposure parameters and potential associations with health outcomes, and determine whether there were other factors that may affect WBV exposures. If there are factors which affect WBV exposures, perhaps interventions can be developed to reduce WBV exposures and subsequently reduce prevalence and severity of LBP among professional truck drivers.

## METHODS

### Subject

A total of 105 professional truck drivers across five different companies were invited to participate in this study, and 96 drivers agreed to participate. The data gathered were baseline measurements for a subsequent randomized controlled trial designed to evaluate two different truck seat suspension systems (Kim *et al.*, 2015). The subjects were all experienced truck drivers with at least 1 year of employment with the current company. The participating drivers were either regional or line-haul drivers, meaning that they spent the majority of their day behind the wheel driving. In addition, all recruited drivers were classified as “no-touch” drivers which meant they did not handle or lift cargo unless absolutely necessary. Among 96 truck drivers, 72 drivers provided their demographic information (Table 1). 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.

**Table 1. Mean (SD) participant demographics (n = 72)**

	Mean	SD
Age (years)	48.2	7.6
Driving experience (years)	18.9	10.7
Weight (kg)	104.9	25.5
Height (cm)	179.4	7.7
BMI	32.3	6.9

## Data collection and analysis

### Whole-body vibration

Per International Organization for Standardization (ISO) 2631-1 WBV standards, a tri-axial seat-pad accelerometer (Model 356B40; PCB Piezotronics; Depew, NY, USA) was mounted on the driver's seat; and either an identical tri-axial or single axis (z-axis) accelerometer (Model 352C33; PCB Piezotronics) was magnetically mounted to the floor of the truck cab beneath the driver's seat (Fig. 1). 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 (6–15 h). Vehicle speed and location were simultaneously recorded at 1 Hz using a GPS logger (Model DG-100; GlobalSat; Chino, CA, USA).

Prior to the data collection, accelerometer calibration was verified using a vibration calibrator (VC21; Metra Mess- und Frequenztechnik; Radebeul, Germany) with vibration magnitudes of 1, 2, 5, and 10  $\text{m s}^{-2}$  (root mean square) at vibration frequencies of 15.9, 80, and 159.2 Hz. The system calibrations were evaluated using a LabVIEW program (v2012; National Instruments; Austin, TX, USA) to analyze and verify accelerometer calibration (Thamsuwan *et al.*, 2013). Based on the accelerometer calibrations, no alternation in the any of the accelerometer gains were necessary across the course of the baseline measurements.

WBV exposures were measured over the truck driver's full shift (6–15 h). The average WBV sampling duration was 11.3 [standard deviation (SD):

4.0] h. According to the GPS data (truck speed  $> 5 \text{ km h}^{-1}$ ), driving time was 6.7 (SD: 2.3) h and nondriving time (truck speed  $< 5 \text{ km h}^{-1}$ ) was 4.6 (SD: 2.9) h. A LabVIEW program (v2012; National Instruments) was used to calculate the WBV exposure parameters per ISO 2631-1 and 2631-5 standards.

There were short episodes where bad or erroneous data were present in the acceleration data that were the result of either signal noise from communication devices in the vehicle cabin, temporary stain-induced shorts in the connectors, or transient shocks saturating and/or overloading the accelerometers. To identify and eliminate the bad or erroneous data, the raw WBV data were analyzed second-by-second and peak, mean and SD values were calculated for each second. Then, based on the data distribution of these parameters, the outlier values for each parameter could be readily identified. This second-by-second analysis indicated that if any 1 s epoch that had a peak, mean or SD value above  $40 \text{ m s}^{-2}$ ,  $\pm 1.0 \text{ m s}^{-2}$  or  $3.2 \text{ m s}^{-2}$ , respectively, likely represented bad data. Using these threshold values,  $< 0.5\%$  of the data was classified as bad data. The remaining good epochs of 1-s data were then analyzed second-by-second and summary measures were calculated. Then, the data were evaluated for important determinants of WBV exposures including brand and year of truck manufacture, age of the truck seat and seat manufacturer (Seat 1 = National Seating; Columbus, OH, USA, Seat 2 = Sears Seating; Davenport, IA, USA). Both continuous (ISO 2631-1) and impulsive (ISO 2631-5) WBV exposure parameters were calculated as follows:

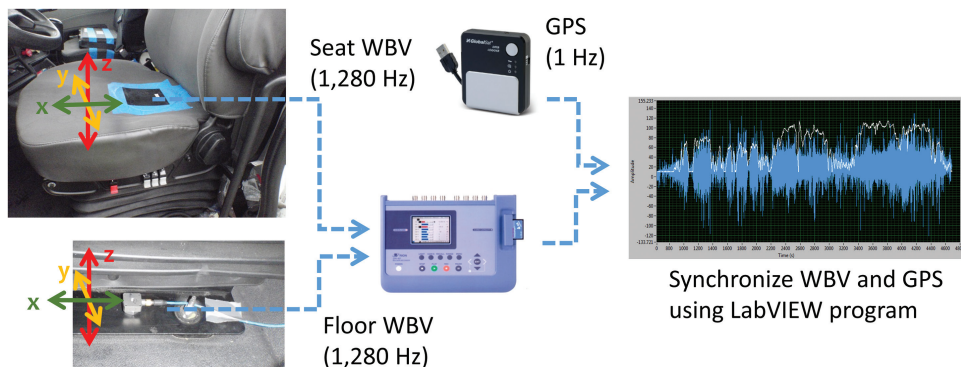


Figure 1 Data acquisition system. Tri-axial accelerometer axes: fore-aft ( $x$ ), lateral ( $y$ ), and vertical ( $z$ ).

ISO 2631-1 parameters

- Root mean square (r.m.s.) weighted average acceleration ( $A_w$ ) calculated at the floor and at the seat pan ( $\text{m s}^{-2}$ ) during the full work shift

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

where  $a_w(t)$ : instantaneous frequency-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 trucks ( $\text{m s}^{-1.75}$ )

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

ISO 2631-5 parameters

- Acceleration dose value ( $D_k$ ) in  $\text{m s}^{-2}$

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

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 ( $\text{m s}^{-2}$ )

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

where  $D_k$ : acceleration dose value in equation (4);  $t_d$ : 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 (4)

$$m_x = 0.015 \frac{\text{MPa}}{\text{m s}^{-2}}$$

$$m_y = 0.035 \frac{\text{MPa}}{\text{m s}^{-2}}$$

$$m_z = 0.032 \frac{\text{MPa}}{\text{m s}^{-2}}$$

To enable comparisons across all measurements, all the parameters ( $A_w, \text{VDV}, S_{ed}$ ) were normalized to reflect 8 h of driving exposure [e.g.  $A(8), \text{VDV}(8)$ , and  $S_{ed}(8)$ ]. The vector sum ( $\Sigma$ ) WBV exposures measured at the seat were also calculated as follows

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

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

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

To assess the WBV exposures across the various WBV standards (ISO 2631-1, ISO 2631-5) and European Union (EU) regulations (European Union, 2002), due to different standard and regulations nomenclature, the following terminology was adopted. Above daily exposure action limits was used to refer to: (i)  $A(8)$  values above  $0.50 \text{ m s}^{-2}$ , the lower limit of the ISO 2631-1 health caution guidance zone and the daily exposure action values in the EU vibration directive; (ii)  $\text{VDV}(8)$  values above  $9.1 \text{ m s}^{-1.75}$ , 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  $0.50 \text{ MPa}$ , 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  $\text{VDV}(8)$  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 h<sup>-1</sup>) and the SEAT(%) calculations were calculated from the data when the truck was moving.

$$\text{SEAT}(\%) = \frac{\text{Parameter value}_{\text{seat}}}{\text{Parameter value}_{\text{floor}}} \times 100 \quad (7)$$

### Health questionnaires

As a part of the 1-year randomized controlled trial study, comprehensive baseline questionnaires were distributed to all of the 105 potential participants to characterize musculoskeletal pain, back function using the Oswestry Disability Index (ODI), and physical and mental health using the 12-item Short Form Survey (SF-12).

Musculoskeletal pain outcomes were collected using a standardized 10-point pain scale adopted from the Standard Nordic Questionnaire (Kuorinka *et al.*, 1987). The scale ranged from 0 to 10 with verbal anchors: 0 being “no pain” and 10 being “worse pain you can imagine.” Drivers were asked to rate the level of their pain when it was at the worst in the past week.

The ODI questionnaire was administered to estimate degree of disability and quality of life (Fairbank and Pynsent, 2000). The ODI questionnaire consists of 10 questions, each of which is scored on a scale of 0–5 with 0 being the least amount of disability and 5 being most severe disability. If nine or more questions were completed, the ODI was calculated as follows

$$\text{ODI} = \frac{\sum_{i=1}^{10} Q_i}{\text{Total possible score}} \times 100 \text{ where } Q_i : \text{score of } i^{\text{th}} \text{ question}$$

0–20	: minimal disability
21–40	: moderate disability
41–60	: severe disability
61–80	: crippling back pain
81–100	: Patients are either bedbound or exaggerating their symptoms

If more than one question were missed, ODI was not calculated. The minimal detectable changes of the ODI with a 90% confidence level is 10%, meaning that change of <10% points may be attributable to error in the measurement.

The SF-12 was used to evaluate the truck driver’s physical and mental health (Ware, 1996). Previous studies have shown that the SF-12 scores are reliable and valid measures to evaluate both physical and mental health status (Ware, 1996; Lim and Fisher, 1999). The SF-12 scores were analyzed by the methods

proposed by Ware *et al.* (2002). Through linear transformation of SF-12 raw scores, eight different health measures (physical function, physical role, bodily pain, general health, vitality, social function, role emotional, and mental health) and two composite summary measures including physical component summary (PCS) and mental component summary (MCS) were calculated using the norm-based methods (Ware *et al.*, 2002). Low scores indicate poor health and significant limitations. Lastly, to identify important determinants of WBV exposures, subject’s demographics and truck information including truck manufacturer, year of truck manufacture, and seat manufacturer were also collected.

### Statistical analysis

The WBV data were summarized with the median and interquartile range (25th, 75th percentile) values due to the non-normality (Altman *et al.*, 1983). Despite the non-normality, as our sample size ( $n = 96$ ) was sufficiently large (central limit theorem), multiple linear regression models (JMP Version 9; SAS Institute; Cary, SC, USA) were used to identify significant determinants affecting the WBV exposures in professional truck drivers. The parametric linear regressions were used since the results were similar to nonparametric tests (Wilcoxon test) as well as linear regressions with log transformed data. The hypothesized explanatory variables included the truck age, the seat age (inferred from truck age), and seat manufacturer. Effect size was calculated using Cohen’s  $d$  (Cohen, 1988). Moreover, Spearman’s rank correlation coefficients (JMP Version 9; SAS Institute) were used to evaluate the relationships between the various WBV exposure measures [A(8), VDV(8), and S<sub>ed</sub>(8)] and the musculoskeletal outcomes. The health outcome measures were summarized and analyzed as suggested by previous studies (Kuorinka *et al.*, 1987; Fairbank and Pynsent, 2000; Ware *et al.*, 2002). Statistical significance was noted when  $P$ -values were less than 0.05.

## RESULTS

### WBV exposures

The full-shift acceleration data were analyzed to characterize the truck drivers’ WBV exposures. The WBV exposures measured on seat and floor from all three axes are summarized in Fig. 2. The A(8) measurements

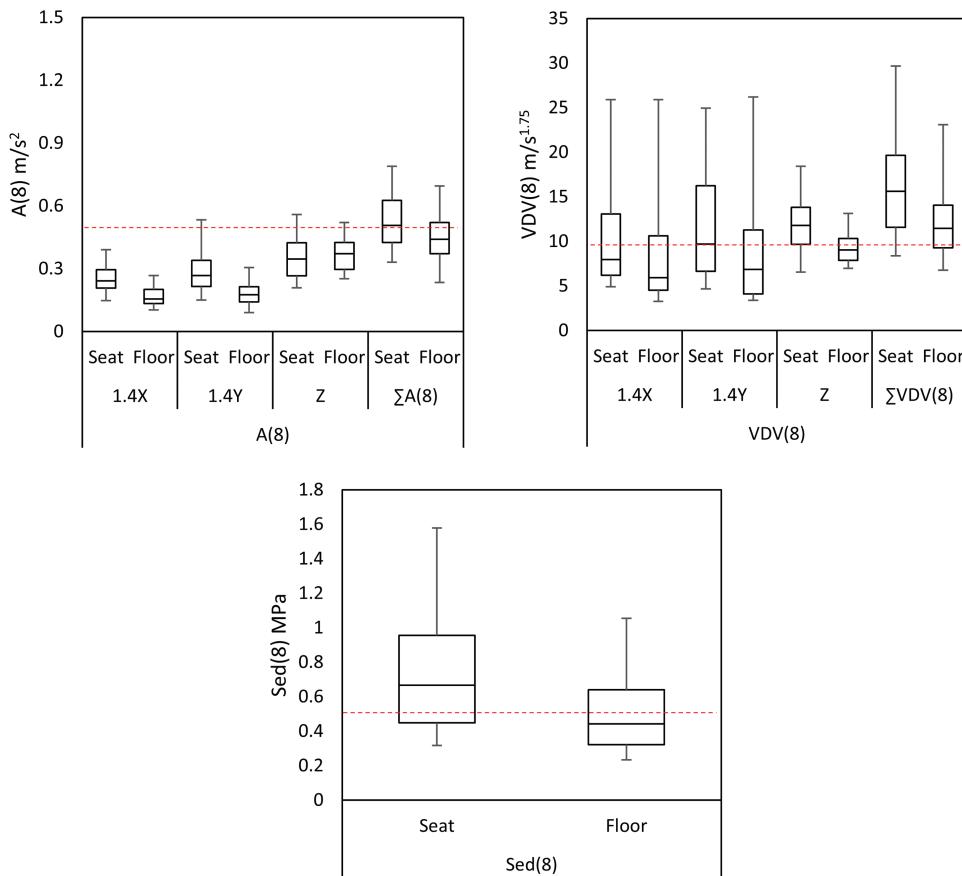


Figure 2 Summary of the full-shift whole-body vibration exposures:  $A(8)$ ,  $VDV(8)$ , and  $S_{ed}(8)$ .  $\Sigma$  indicates the vector sum of all three axes. The boxes indicate interquartile ranges; the horizontal lines in the boxes are median values; and whiskers indicate maximum and minimum values. The red dotted lines represent the daily exposure action limits:  $A(8) = 0.5 \text{ m s}^{-2}$ ;  $VDV(8) = 9.1 \text{ m s}^{-1.75}$ ;  $S_{ed}(8) = 0.5 \text{ MPa}$ . The SEAT measurements were based on 96 observations and the floor measurements were  $n = 59$  for  $x$ ,  $y$  and  $\Sigma$  and  $n = 96$  for the  $z$ -axis because the floor WBV exposures were measured using either tri-axial ( $n = 59$ ) or single  $z$ -axis ( $n = 37$ ) accelerometers.

from the seat over the full-shift showed that the vertical ( $z$ ) axis was the predominant axis of exposure and the corresponding exposures (Median [25th, 75th percentile]:  $0.35 [0.27, 0.42] \text{ m s}^{-2}$ ) were below the ISO and EU daily exposure action limits ( $0.5 \text{ m s}^{-2}$ ). However, vector sum  $A(8)$  exposures ( $0.51 [0.43, 0.63] \text{ m s}^{-2}$ ) were above the daily exposure action limits (Fig. 2). The SEAT results revealed that  $z$ -axis  $A(8)$  values were  $0.86$  indicating that  $\sim 86\%$  of the floor-measured vibration was transmitted to the drivers.

As shown in Fig. 2, the average seat-measured  $VDV(8)$  values ( $1.4x = 8.0 [6.2, 13.1]$ ;  $1.4y = 9.7 [6.6, 16.2]$ ;  $z = 11.8 [9.7, 13.8] \text{ m s}^{-1.75}$ ) were above the ISO and EU daily exposure action limits ( $9.1 \text{ m s}^{-1.75}$ ). The SEAT value for  $z$ -axis  $VDV(8)$  exposures was

$0.95$ , indicating the seats attenuated only 5% of the impulsive WBV exposures. The seat-measured daily equivalent static compression dose,  $S_{ed}(8)$  value ( $0.67 [0.45, 0.96] \text{ MPa}$ ) was higher than  $0.5 \text{ MPa}$ , indicating that the probability of an adverse health effect at life time exposure may be considerably high based on the whole route WBV exposure data.

#### Factors influencing WBV exposures

Using the GPS data, the WBV data while the trucks were in motion (i.e. faster than  $5 \text{ km h}^{-1}$ ) was identified and analyzed to determine whether the hypothesized explanatory variables including truck manufacturer, truck age, seat age, and seat manufacturer affected the WBV exposures. While truck manufacturer had

little effect on WBV exposures, truck/seat age and seat manufacturer appeared to influence WBV exposures.

The seat-measured WBV exposures differed between the two major seat manufacturers with no differences in the WBV measures from the floor (Table 2). The z-axis SEAT values provide the best means to compare seat performance as the SEAT values account for the differences in the WBV values measured at the floor of the vehicle. When the z-axis SEAT values [A(8) and VDV(8)] were compared between seats, Seat 2 (Sears Seating) transmitted less vibration to the seat of the operators compared to Seat 1 (National Seating). Spearman's  $\rho$  ( $Y_s$ ) showed that truck age was not correlated with the floor-measured z-axis A(8) ( $Y_s = -0.1$ ;  $P = 0.32$ ) and VDV(8) exposures ( $Y_s = -0.08$ ;  $P = 0.45$ ) whereas truck age was negatively correlated with the seat-measured z-axis A(8) ( $Y_s = -0.33$ ;  $P = 0.01$ ) and VDV(8) ( $Y_s = -0.24$ ;  $P = 0.02$ ).

#### Health outcomes

Among 105 invited participants, 69 drivers completed the baseline questionnaires (response rate: 65.7%). LBP was the most prevalent musculoskeletal symptom (prevalence: 72.5%) with the average pain score of 2.9 on a 10-point scale (Table 3). More than half of

the truck drivers expressed current neck (50.7%) and shoulder pain (55.1%). The ODI (mean: 14.2%, SD: 2.1) indicated that truck drivers had minimal disability as it fell within the 0–20% range.

Among the 69 drivers who completed the baseline questionnaires, full SF-12 health surveys were completed by 42 of the drivers. The overall health status of the professional truck drivers was similar to the general population (Fig. 3). However, the truck driver's bodily pain score and PCS scores were significantly lower than the general populations' scores ( $P = 0.01$  and  $0.04$ , respectively).

The SF-12 norm-based scores were compared across WBV exposure tertiles among the low ( $A(8) < 0.33 \text{ m s}^{-2}$ ), medium ( $0.33 < A(8) < 0.45 \text{ m s}^{-2}$ ), and high ( $A(8) > 0.45 \text{ m s}^{-2}$ ) WBV exposure groups (Fig. 4). There was no difference in demographic data between the three WBV exposure groups ( $P_s > 0.09$ ). The low WBV exposure group had significantly higher physical function ( $50.0 \pm 2.4$ ;  $P = 0.03$ ) and role physical scores ( $53.3 \pm 1.9$ ;  $P = 0.01$ ) compared to the high WBV exposure group (physical function:  $39.9 \pm 2.3$ ; role physical:  $41.2 \pm 2.4$ ). There were no trends or differences in the SF-12 norm-based scores when the VDV(8) exposures were categorized across WBV exposure tertiles.

**Table 2. Comparisons of median [interquartile] WBV measures between the two major seat manufacturers along with the associated effect sizes and P-values**

Parameter	Location	Axis	Seat 1 [n = 70]	Seat 2 [n = 26]	Effect size [95% CI]	P-value
A(8), $\text{m s}^{-2}$	Floor	z	0.47 [0.40, 0.53]	0.41 [0.37, 0.45]	-0.27 [-0.73, 0.19]	0.21
	Seat	z	0.42 [0.34, 0.49]	0.30 [0.25, 0.38]	-0.78 [-1.25, -0.31]	<b>&lt;.0001</b>
	SEAT	z	91.0% [80.1, 103.7]	77.9% [67.9, 87.8]	-1.11 [-1.74, -0.49]	<b>0.01</b>
VDV(8), $\text{m s}^{-1.75}$	Floor	z	10.3 [9.3, 11.2]	8.9 [8.2, 9.5]	-0.4 [-0.86, 0.06]	0.14
	Seat	z	9.9 [8.3, 11.5]	7.0 [6.1, 9.2]	-0.89 [-1.37, -0.42]	<b>0.01</b>
	SEAT	z	97.3% [83.2, 109.8]	82.7% [66.2, 100.5]	-0.55 [-1.16, 0.05]	0.05

A(8) = average weighted vibration; VDV(8) = vibration dose value. Effect size is Cohen's d. Statistical differences are denoted by bold letters.

**Table 3. Self-reported musculoskeletal pain outcomes among the truck drivers. A 10-point scale was used with 0 indicating no pain and 10 the worse pain you can imagine ( $n = 69$ )**

Location	N	Prevalence (%)	Mean	SD	95% CI
Low back	50	72.5	2.9	2.0	[2.4, 3.4]
Shoulder	38	55.1	2.9	2.5	[2.3, 3.4]
Neck	35	50.7	2.7	2.4	[2.1, 3.3]
Knee	29	42.0	2.4	2.5	[1.8, 3.0]
Wrist/forearm	25	36.2	2.2	2.6	[1.6, 2.8]
Ankle/feet	22	31.9	1.7	2.3	[1.2, 2.2]
Leg pain/sciatica	18	26.1	1.4	2.2	[0.9, 1.9]

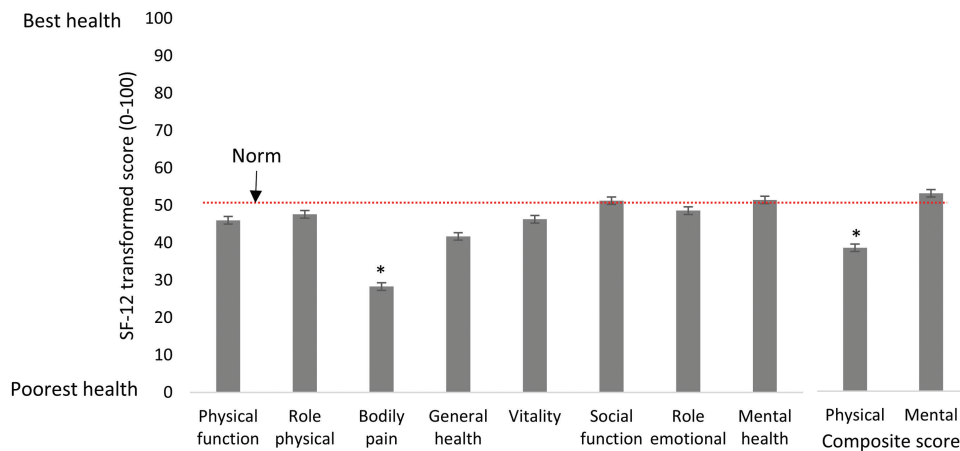


Figure 3 SF-12 norm-based scores, physical and mental composite scores among the truck drivers ( $n = 42$ ). The red line represents the average SF-12 score of the general US population. The SF-12 norm-based scores above the norm indicate better health status than the general US population whereas the scores below the norm indicate a worse health status. The asterisks indicate a significant difference from the general population.

#### Associations between WBV exposure measures and health outcomes

Spearman's rank correlation coefficients ( $Y_s$ ) between the WBV summary measures (predominant z-axis and vector sum) and health outcomes (LBP, neck/shoulder pain, ODI, and SF-12 health scores) are summarized in Table 4. The predominant z-axis time weighted average WBV measure,  $A(8)$  was positively correlated with LBP ( $Y_s = 0.31; P = 0.05$ ) and shoulder pain ( $Y_s = 0.44; P = 0.006$ ). The vector sum time weighted average WBV measure,  $\Sigma A(8)$  was also positively correlated with shoulder ( $Y_s = 0.38; P = 0.02$ ) and neck pain ( $Y_s = 0.36; P = 0.04$ ) but not back pain ( $Y_s = 0.29; P = 0.069$ ). The SF-12 health scores showed

that predominant z-axis  $A(8)$  was negatively correlated with physical function ( $Y_s = -0.47; P = 0.003$ ), role physical ( $Y_s = -0.51; P = 0.001$ ), and physical component summary score ( $\rho = -0.39; P = 0.02$ ). In general, these results indicated that the average WBV exposures [ $A(8)$  and  $\Sigma A(8)$ ] were associated with negative health whereas no associations were found for  $VDV(8)$ . However, the ODI was not correlated with any of the WBV exposure measures (Table 4).

#### DISCUSSION

Using the preintervention baseline data collected as a part of a randomized controlled trial, the main goal of the present article was to evaluate WBV,

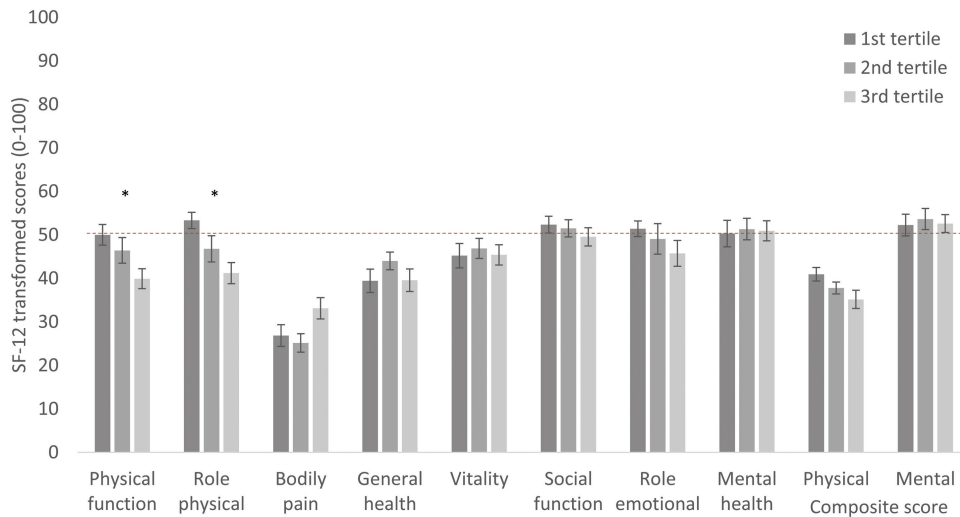


Figure 4 Comparisons of SF-12 norm-based scores among low [ $A(8) < 0.33 \text{ m s}^{-2}$ ], medium [ $0.33 < A(8) < 0.45 \text{ m s}^{-2}$ ], and high [ $A(8) > 0.45 \text{ m s}^{-2}$ ] WBV exposure groups ( $n = 13, 13, 14$ , respectively). The red line represents the average SF-12 score of the general US population. The asterisks indicate the significant difference between the groups.

Table 4. Spearman's rank correlation coefficients ( $Y_s$ ) between WBV exposure measures and pain and SF-12 outcomes

	z-axis		Vector Sum			
	A(8)	VDV(8)	$\sum A(8)$	$\sum VDV(8)$	$S_{ed}(8)$	
LBP	<b>0.31</b>	0.07	0.29	0.22	-0.01	
Shoulder pain	<b>0.44</b>	0.11	<b>0.37</b>	0.07	-0.08	
Neck pain	0.24	0.15	<b>0.36</b>	0.25	0.18	
ODI	0.22	-0.06	0.16	-0.09	0.09	
PF	<b>-0.47</b>	-0.20	-0.28	-0.02	-0.02	
RP	<b>-0.51</b>	-0.22	<b>-0.44</b>	0.10	0.00	
BP	0.27	0.03	0.30	-0.12	-0.11	
GH	-0.04	0.05	0.18	0.10	-0.01	
SF-12	VT	-0.05	0.13	-0.02	0.03	0.21
SF	-0.15	0.03	-0.11	0.09	0.19	
RE	-0.23	-0.14	-0.18	0.06	0.14	
MH	-0.04	0.03	0.00	0.10	0.14	
PCS	<b>-0.39</b>	-0.19	-0.22	-0.12	-0.23	
MCS	-0.01	0.05	-0.06	0.10	0.23	

PF, physical function; RP, role physical; BP, bodily pain; GH, general health; VT, vitality; SF, social function; RE, role emotional; MH, mental health; PCS, physical component summary; MCS, mental component summary. Bold numbers indicate significance at  $\alpha = 0.05$ .

musculoskeletal and general health outcomes, and their relationships. Based on the baseline questionnaire responses, LBP had the highest prevalence (72.5%) and the physical health of the truck drivers was found to be below US averages. Analysis of the WBV data revealed that truck drivers were exposed to moderate to high levels of WBV with vector sum exposures above ISO and EU daily exposure action limits. The study also found that WBV exposures were significantly affected by truck seat age and the seat manufacturer. Lastly, although impulsive exposures [VDV(8) and  $S_{ed}(8)$ ] were more prominent than average exposures [A(8)], the A(8) WBV exposures had stronger relationships with the musculoskeletal health outcomes than the impulsive WBV exposure parameters.

#### WBV exposures in semi-truck driving

As shown in Fig. 2, the predominant z-axis A(8) values measured over the whole route were acceptable based on the ISO and EU daily exposure action limit ( $0.5 \text{ m s}^{-3}$ ); however, the vector sum A(8) values were above the action limits. This substantial difference in risk prediction between the predominant z-axis and vector sum WBV exposures indicates that it may be important to include the vector sum exposures as supplemental measures to the predominant-axis measures as discussed by Bovenzi *et al.* (2006).

One concern with the ISO 2631-1 standard is multiplying the  $x$ - and  $y$ -axis by a factor of 1.4 for health effects, this 1.4 multiplier was based on research conducted on a small group of subjects back in the 1960s (Milwa, 1967a, 1967b). Arguments have been made for and against the use of the 1.4 multiplier and our practice has been to use the 1.4 multiplier for consistency to enable comparisons across our studies. The 1.4 multiplier did not affect our predominant axis determination but increased our vector sum exposure estimates. Future research and future versions of the ISO 2631-1 standard should seek to clarify the use of the 1.4 multiplier and interpretation of the vector sum exposures in the context of evaluating whether ISO daily action and exposure limits have been reached or exceeded.

The results also demonstrated that VDV(8) and  $S_{ed}(8)$  exposures were above the EU and ISO daily exposure action limits (VDV(8) =  $9.1 \text{ m s}^{-1.75}$ ;  $S_{ed}(8) = 0.5 \text{ MPa}$ ), indicating that truck drivers must be experiencing impulsive shocks during their regular

work. As indicated by VDV(8), the highest maximum transient shocks were in the  $x$ - and  $y$ -axes which was likely associated with coupling and decoupling of trailers. Previous studies have shown that exposures to the transient shock components could contribute to the degeneration of lumbar spine more than the continuous steady state component (Mayton *et al.*, 2008). Moreover, the truck seat suspension appeared to have limited performance attenuating the impulsive VDV(8) exposures (Table 2). This is in line with previous studies (Paddan and Griffin, 2002; Thamsuwan *et al.*, 2013) that demonstrated that vehicle seats had limited performance in attenuating the WBV exposure. This limited seat performance may be due to the fact that industry-standard air-suspension seats cannot react fast enough to external vibration and lack the requisite stiffness to absorb impulsive transient shocks when the vehicle is travelling at moderate to high speeds.

#### Factors affecting the WBV exposures

This study also found that the WBV exposures are affected by the seat age and the seat manufacturer. The SEAT values for A(8) and VDV(8) were significantly higher in Seat 1 (National Seating) when compared to Seat 2 (Sears Seating), indicating that Seat 1 had better vibration attenuation performance (Table 2). Previous studies have shown that the vibration attenuation performance can depend on the seat type (Blood *et al.*, 2010a, 2010b, 2015; Jonsson *et al.*, 2014). Moreover, the results demonstrated that the WBV exposures measured from the seat were negatively correlated with truck age even though no correlation was found between the floor-measured WBV exposures and truck ages. This finding indicates that seat suspension performance may deteriorate over time whereas truck suspension performance may not change with age. Therefore, periodic seat maintenance or seat replacement may be merited to reduce the potential for increases in WBV exposures related to seat wear-and-tear. These findings can be used to help trucking companies or drivers plan the seat maintenance or replacing old seats.

#### Health outcomes and disability index

Musculoskeletal pain scores on the seven different locations showed that LBP was the most prevalent musculoskeletal symptoms (prevalence: 72.5%) with

the average pain score of 2.9 (Table 3). This LBP prevalence appears to be consistent with previous findings showing that the LBP prevalence of professional drivers ranges from 50 to 80% (Brendstrup and Biering-Sorensen, 1987; Riihimaki *et al.*, 1989; Schwarze *et al.*, 1998; Bovenzi *et al.*, 2002, 2006; Bovenzi, 2009). Given the fact that the prevalence of LBP in the general population not exposed to WBV to be around 30% (Bongers and Boshuizen, 1990), this higher prevalence of LBP among truck drivers implies that some aspect or aspects of their work contributes to LBP. The physical components of the SF-12 results indicated physical health outcomes decreased as WBV exposures increased. Also, more than half of the truck drivers expressed current neck (50.7%) and shoulder pain (55.1%). The prevalent pain in the neck and low back supports the previous findings that the WBV exposures affect the spinal systems through muscular fatigue (Wilder *et al.*, 1996) and degeneration of the spine (Hulshof and van Zanten, 1987; Bovenzi and Hulshof, 1999).

The average ODI was 14.2% (SD: 12.8), indicating that truck drivers had minimal disability (range 0–20%). This index was originally used for pre- and post-surgical assessment so the scale may be less sensitive for measuring and detecting changes in occupationally related LBP. The Roland Morris Disability Index (Roland and Morris, 1983) has been used in occupational studies so in the future the use of the RMD may be merited. Despite the low disability index, the SF-12 health scores showed that the truck driver's physical health status was worse than the general population (Fig. 3). This result is consistent with higher injury rates and workers compensation claim costs experienced in the trucking sectors (Rauser *et al.*, 2008; Spielholz *et al.*, 2008; BLS, 2014). Therefore, as the WBV is one of the major physical exposures linked to various musculoskeletal injuries among truck drivers, it will be important to develop effective engineering interventions to reduce the WBV exposures in truck driving.

#### WBV exposures and health outcomes

The ISO standard and EU directive provides daily exposure action values and daily exposure limit values on A(8) and VDV(8) to estimate injury risks. Although most EU countries use A(8) as WBV exposure value, some limitations of using a single exposure value to estimate the risks of injuries have been identified (Bovenzi,

2009). Therefore, this study evaluated the relationships between the different WBV summary measures and health to determine which WBV exposure measures are related to the health outcomes (Table 4). The results showed that the predominant, z-axis A(8) values were positively correlated with the low back and shoulder pain. The  $\Sigma A(8)$  values were positively correlated with shoulder and neck pain. Moreover, the results indicated that the higher A(8) exposure values were correlated to lower physical functionality in the SF-12 outcomes. The comparisons of SF-12 scores between A(8) tertiles demonstrated that the low WBV exposure group generally had better physical functionality compared to the high WBV exposure group despite the lack of a difference in demographic data between these two groups. Although the tertile comparisons of VDV(8) showed a similar trend on physical functionality, it did not reach statistical significance. These results indicate that the A(8) and  $\Sigma A(8)$  may be good exposure measures and support the practice of European countries utilizing A(8) as the preferred measure of daily WBV exposure. However, a limitation and caution to this interpretation is the cross-sectional assessment of the WBV exposures and health outcomes. A prospective study (Bovenzi *et al.*, 2009) showed that VDV(8) and exposure duration were better indicators of LBP than A(8). Therefore, further epidemiological studies to validate these findings would be merited. Randomized controlled trials to evaluate the efficacy of different seats in reducing WBV exposures and measuring the associated effects on LBP will more thoroughly assess the association between WBV and LBP.

#### Limitations

A strength of our study is that we collected 96 WBV measurements during the drivers' full shift (6–15 h). This provides a more representative picture of WBV exposure compared to previous studies that have typically examined WBV exposures for short periods of time from either simulated or standardized routes. The WBV exposure and pain data were collected relatively at the same time; thus, potential bias due to time lag between exposure and response data collection was minimized. However, this study does have some limitations. Even though we noted the possible relationships between lower WBV exposures and lower LBP, this result cannot be interpreted as a causal relationship because these results are based on

the cross-sectional analysis with an assumption that drivers have experienced the current WBV exposures throughout their career. Therefore, subsequent prospective studies to further evaluate this association are merited. Moreover, as only 42 drivers filled out the SF-12 health survey, nonresponse bias may affect the survey results. However, the comparisons between response and non-response groups showed no differences in their exposures to WBV. Therefore, the non-response bias may be negligible. Lastly, since it was a field base study, many predictor variables including truck model, year, road type, truck seat, etc. could neither be controlled nor balanced. Therefore, a careful interpretation of the study results may be merited until a laboratory-based experiment validates the effects of those factors in WBV exposures.

### CONCLUSIONS

The truck drivers in this study had moderate to high exposures to WBV. The vector sum  $A(8)$  exposures were above daily action limits whereas the predominant z-axis exposures, as advocated by the EU, were below action limits. In addition, the impulsive  $VDV(8)$  and  $S_{ed}(8)$  exposures were more prominent (above the action limit) than the average vibration exposures,  $A(8)$ . Moreover, the significant WBV exposure contrast by seat age (inferred from truck age) indicates that periodic replacement of truck seats would reduce a truck driver's exposure to WBV. Finally, based on the correlation between the WBV exposure and health outcomes, this study indicates that the predominant-axis  $A(8)$  or vector sum  $A(8)$  may have a stronger link to musculoskeletal (LBP) and other adverse health outcomes than the impulsive  $VDV(8)$  or  $S_{ed}(8)$  measures.

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