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Whole body vibration exposures in forklift operators: comparison of a mechanical and air suspension seat

Ryan P. Blood, James D. Ploger and Peter W. Johnson*

School of Public Health, Department of Environmental and Occupational Health Sciences, University of Washington, Seattle, WA 98105–6099, USA

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Using a repeated measures design, this study compared differences in whole body vibration (WBV) exposures when 12 forklift operators drove the same forklift with a mechanical suspension and an air suspension seat. A portable PDA-based WBV data acquisition system collected and analysed time-weighted and raw WBV data per ISO 2631-1 and 2631-5 WBV measurement standards. Tri-axial measurements of weighted vibration (A_w), crest factor, vibration dose values, time-weighted average-peak, raw (+) peak, raw (–) peak and static compression dose (S_{ed}) were compared between seats. There were significant differences in z-axis WBV exposures with the air suspension seat, yielding lower WBV exposures. In addition, there were differences between seats in how they attenuated WBV exposures based on the driver's weight. In the mechanical suspension seat, WBV exposures were weight-dependent, with lighter drivers having higher WBV exposures, whereas with the air suspension seat, the same trends were not as prevalent.

Statement of Relevance: This study contributes to the understanding of how different seat suspensions can influence WBV transmission and how some components of vibration transmission are dependent on the weight of the driver. Additional systematic studies are needed to quantify how various factors can influence WBV exposures.

Keywords: back pain; injury risks; intervention effectiveness; musculoskeletal disorders; vehicle ergonomics

1. Introduction

Epidemiological studies have shown a relatively strong association between occupational low back pain (LBP) and the exposure to whole body vibration (WBV) (Pope *et al*. 1991, Bernard 1997, National Research Council 2001) with the risks for injury increasing as the duration and dose of WBV increases (Teschke *et al*. 1999). Focusing specifically on heavy equipment vehicle (HEV) operators, a recent meta-analysis found the relative risk for LBP in HEV operators to be 2.21, indicating that HEV operators are at more than twice the risk of developing LBP in comparison with non-HEV operators (Waters *et al*. 2008). Although the exposure–response relationship between WBV and back disorders is currently not well understood (Chen *et al*. 2003), the current body of research indicates that there is a causal relationship between WBV exposure and LBP among vehicle operators (Bovenzi 1996). Complicating the problem of determining the link between WBV exposure and LBP outcomes, exposure to WBV and physical loading factors, such as lifting, manual material handling (MMH) activities, and posture are also important components of the multi-factorial origin of injury (Bovenzi *et al*. 2006, Okunribido *et al*. 2008). Drivers and operators with MMH job duties have been shown to have a higher prevalence of LBP despite having shorter WBV exposure duration than drivers without MMH job tasks (Robb and Mansfield 2007).

In a recent review of the epidemiological research, studies involving forklift operators have shown that there is a significant relationship between working as a forklift operator and the development of LBP (Waters *et al*. 2008). In a study examining the prevalence of LBP and exposure to WBV among port machinery workers, forklift operators were found to have significantly higher exposures than other machinery operators and had a higher prevalence of LPB (Bovenzi *et al*. 2002).

A number of spinal injury mechanisms have been associated with WBV exposures, including structural damage to the bony endplate of the lumbar vertebral body (International Organization for Standardization 2004). Fatigue-induced micro-fractures have been reported for *in vitro* lumbar vertebral endplates, which may lead to subsequent disc degeneration (Sandover 1983, Brinckmann *et al*. 1987, Hansson *et al*. 1987). Biomechanical and biological research has found that

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*Corresponding author. Email: petej@uw.edu

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WBV elevates spinal load (Fritz 1997, 2000), causes muscle fatigue in the supporting musculature (Wilder *et al.* 1996) and is linked to the thinning of the intervertebral discs and subsequent disc herniations (Griffin 1990, Thalheimer 1996). Chronic vibration exposure, specifically in occupational settings, can lead to histological changes in cartilage, discs, muscle and bone. The onset of LBP may be gradual and insidious, which is very different from the acute presentation of back pain associated with MMH and lifting tasks (Wilder and Pope 1996). The onset of WBV can also adversely affect musculoskeletal, cardiovascular, cardiopulmonary, metabolic, endocrinological, nervous and gastrointestinal systems of the body (Thalheimer 1996). Some of these disorders may be more strongly associated with impulsive exposures. Occupational WBV exposure has also been shown to have a negative influence on work performance, specifically disruptive to perceptual tasks (Conway *et al.* 2007).

Impulsive shocks are suspected to be particularly damaging to the health of persons exposed to WBV. However, the current methodology for accurately quantifying the measurement, damage mechanism and health effects of impulsive shocks is still evolving (Waters *et al.* 2007). Examples of multiple impulsive shocks include machinery traveling over rough surfaces, such as pot holes, vehicles travelling over speed bumps and small boats impacting waves in rough seas. Long-term exposure to vibration containing multiple shocks has an adverse effect on the health of the bony endplate of the lumbar vertebral body (International Organization for Standardization 2004). Recent research has illustrated that, in the short term, subjects have reported discomfort when exposed to multiple vertical shocks (Ahn and Griffin 2008).

All current WBV standards specify that vibration measurements be made in each of the three applicable axes (x, y and z) in order to account for the vector nature of vibration, which involves both a magnitude and a direction (International Organization for Standardization 1997). WBV exposures with impulsive content can substantially affect the exposure metrics specified in ISO 2631-1 (Griffin 1998, Lewis and Griffin 1998) and may underestimate true exposure levels. To address the limited guidance available regarding impulsive WBV exposures in ISO 2631-1, the International Organization for Standardization adopted a new standard: *Evaluation of human exposure to whole-body vibration – Part 5: Method for evaluation of vibration containing multiple shocks* (International Organization for Standardization 2004). This standard specifies that WBV measurements be made using similar protocols to those outlined in ISO 2631-1, with the exception that the raw vibration signal is collected continuously at a high frequency and a cumulative acceleration dose (D_k) is calculated for each axis. The D_k values are then used to compute a daily equivalent static compression dose (S_{ed}) to the spine. The S_{ed} was developed as part of ISO 2631-5 and is based on biomechanical models that have shown a linear relationship between shocks, acceleration and the ability to predict deterioration of the spine (International Organization for Standardization 2004). Currently, the long-term health outcomes resulting from repeated impulsive shock exposures are not well understood.

Prior research has compared the performance of seat suspensions and their ability to attenuate continuous low frequency and impulsive high frequency WBV exposures. Research has shown that passive suspension systems have produced promising results attenuating vibration (Hostens *et al.* 2004). In addition, seated posture and seat design also significantly affect the transmission of WBV to the spine (Makhsous *et al.* 2005).

There is a wide array of seats available for most commercially operated vehicles and equipment. The two major classes of seats that can be installed in these vehicles consist of either an air suspension or a mechanical suspension. Forklift drivers are one class of equipment operators whose vehicles can be purchased and equipped with either type of seat suspension. Using a group of experienced forklift drivers and calculating time-weight average (TWA) and impulsive WBV exposure parameters, the purpose of this study was to characterise and determine whether there were differences in WBV exposures between a mechanical suspension and an air suspension seat. If there are differences in WBV attenuation between seats, then this may guide the selection and purchase of seats for forklifts and similar types of vehicles.

2. Research methods

This study examined the exposure to WBV using two different seats: a mechanical suspension seat (model MSG-65; Grammer AG; Amberg, Germany); an air suspension seat (model MSG-75; Grammer AG). To enable a controlled comparison, both seats used in the study were brand new and made by the same manufacturer. As shown in Figure 1, the seats were similar in appearance. However, due to differences in the design of the suspension system, the mechanical suspension seat had 20 mm of travel compared with 30 mm of travel in the air suspension seat. Using a repeated measures design, subjects all drove the same forklift (Model Hyster S80; NACCO Materials Handling Group, Inc., Portland, OR, USA) under two conditions: 1) during 1 h of actual work; 2) over a standardised test route. The standardised test route, which was 3.5 km in length, consisted of a variety of outdoor paved surfaces, transitions and a smooth concrete floor within a large building. The seat order during the testing was randomised.

2.1. *Subjects*

A total of 12 experienced forklift operators participated in the study. The mean (SD) age, weight and BMI of the subjects was 44.3 (±11.6) years, 98.3 (±19.4) kg and 31.0 (±4.7), respectively. On average, subjects had 17.7 (±13.9) years of experience operating forklifts. All subjects gave their informed consent and all testing procedures were approved by the Human Subject Committee at the University of Washington.

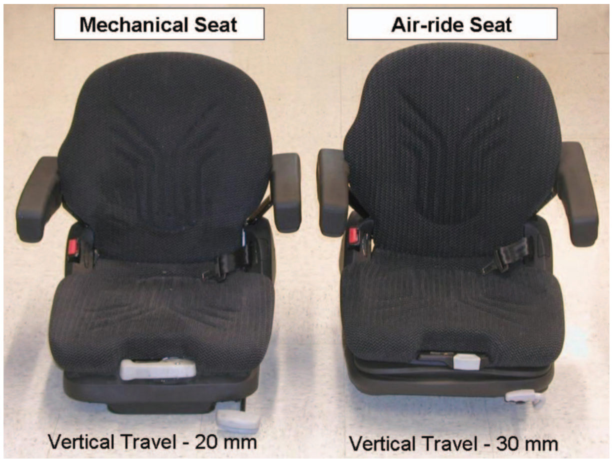

Figure 1. Mechanical suspension seat and air suspension seat.

2.2. *Instrumentation*

Figure 2 shows the schematic and set-up of the WBV data collection system including synchronisation and integration. A PDA-based (model H5555; Hewlett-Packard, Houston, TX, USA) portable WBV data acquisition system was used to collect raw, unweighted tri-axial WBV measurements at 640 Hz per channel. With six channels, a total of 3840 samples were collected per second. The data acquisition system allows for the simultaneous collection of TWA data stored on the data logger (model HVM 100; Larson Davis, Depew, NY, USA) along with the raw, unweighted data stored on the PDA. A seat pad ICP accelerometer (model 356B40; PCB Piezotronics; Depew, NY, USA) with a frequency response of 0.5 to 1000 Hz was mounted on the driver's seat and an identical accelerometer was securely mounted on the floor of the forklift adjacent to the base of the forklift driver's seat. No anti-alias filtering was implemented.

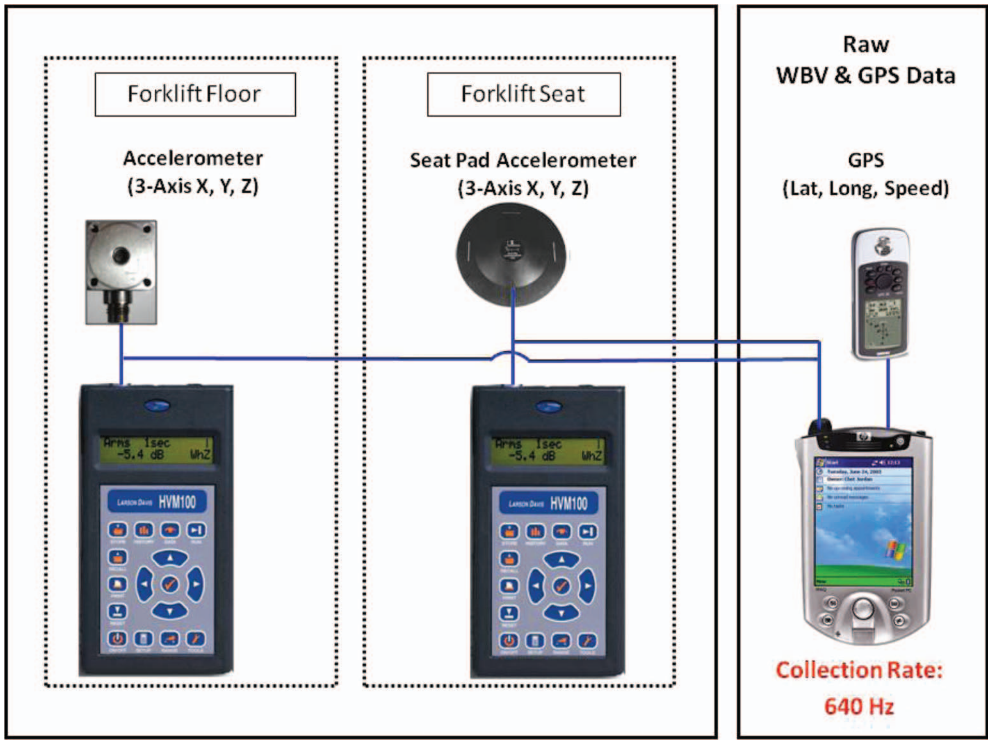

Figure 2. Schematic of whole body vibration (WBV) data collection system. GPS = global positioning system.

Power spectral densities on the raw, unweighted vibration data indicated that the majority of the frequency content from the seat-mounted accelerometer was below 30 Hz and there was virtually no power above 110 Hz. The frequency content was higher in the floor-mounted accelerometer with the majority of the frequency content below 80 Hz with very little power above 275 Hz.

As shown in Figure 2, two HVM 100 data loggers were used as accelerometer amplifiers. A T- connector was put on each of the accelerometer cables with one cable going to the HVM 100 and the other cable carrying the raw, unweighted vibration signals to a BNC connector block (Model BNC-2110; National Instruments, Austin, TX, USA). The BNC connector block (not shown in the figure) transferred the signals to a 16 bit National Instruments data acquisition card (Model 6036E; National Instruments) connected to the PDA. Using a LabVIEW PDA software, a LabVIEW program was written and downloaded to the PDA. The LabVIEW PDA program stored the raw WBV data in real time to a 2 gigabyte secure digital memory card in the PDA. In addition, using the serial port on the PDA, once every second, global positioning system (GPS) data were also collected with a GPS receiver (GPSmap76; Garmin, Olathe, KS, USA). The LabVIEW PDA program integrated and stored the GPS data with the WBV data so the location and velocity of the forklift could also be analysed in parallel.

2.3. Data collection

The data collection for this study was accomplished in two distinct phases. The first phase required subjects to perform their normal work tasks for 1 h; this work activity varied depending on the assignments given to the subjects during the hour. Phase 1 was devised to accurately collect a real work exposure during a forklift operator's normal day. Since the forklift seats did not allow the operators to rotate the seat away from the forward facing direction, the dominant direction of travel during their normal work was forward, roughly 10% of the work time involved travel in reverse using the rear-view mirrors to navigate.

The second phase of data collection was controlled by the data collection staff. The forklift operators were asked to drive a standardised route around the facility, which included a variety of road surfaces that attempted to simulate exposures as drivers travelled around the facility. The standardised route required approximately 12–15 min driving time depending on traffic around the facility and included exclusively travel in the forward direction.

2.4. Data analysis

The continuous data collected on the PDA was downloaded after each run to a PC and input into a LabVIEW routine (LabVIEW version 7.1; National Instruments), which appropriately weighted the continuous signals (Zuo and Nayfeh 2003). As outlined in ISO 2631-1-1997 and 2631-5-2004, WBV exposures were then calculated from the two phases of data collection, the 1 h of actual work and standardised route.

The ISO 2631-1 parameters calculated included:

Root mean square average weighted vibration (A_w) – calculated at the floor and at the seat pan of the forklift (m/s^2).

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

TWA peak – the highest magnitude of A_w measured during the measurement period (m/s^2). 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 forklift (m/s$^{1.75}$).

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

The ISO 2631-5 parameters calculated included: Average daily dose (D_k) – is designed to be an estimate of daily vibration dose (m/s^2).

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

Static compressive dose (S_{ed}) – measured in megapascals (MPa), which has been developed through biomechanical modelling to capture the linear relationship between peak acceleration and input shocks to responses in the spine.

$$S_{ed} = \left[\sum_{k=x,y,z} (m_k\, D_{kd})^6\right]^{\frac{1}{6}} \tag{4}$$

All parameters (A_w, VDV, D_k, S_{ed}) were normalised to reflect the WBV exposures if the forklifts were operated for an 8 hour day. In addition, other parameters were extracted from the raw data including:

Raw (+) peak – the highest positive peak from the raw weighted vibration (m/s^2).
Raw (–) peak – the highest negative peak from the raw weighted vibration (m/s^2).

Finally, seat effective amplitude transmissibility (SEAT) factors were calculated. The SEAT value provides a measure of how well the seat attenuates the spectrum of vibration relative to vibration energy transmitted to the base of seat at the floor of the vehicle (Paddan and Griffin 2002). The calculation of the SEAT value for A_w and VDV, as well as the other vibration attenuation factors, is shown below:

$$SEAT\ value\ or\ Attenuation\ Ratio\ (\%) = \frac{parameter\ value_{seat}}{parameter\ value_{floor}} \times 100 \tag{5}$$

2.5. *Statistical analyses*

Repeated-measures ANOVA methods were used to determine whether the seats attenuated exposures and whether there where WBV exposure differences between the mechanical and air suspension seats. In addition, the WBV exposures collected during the standardised route were also compared with the 1 h of actual work. Finally, due to the small sample sizes, non-parametric Wilcoxon rank-sum tests were used to determine whether there were differences in WBV exposures as a function of driver weight. Weight classes were selected to get an even distribution across forklift operators and grouped the subjects into light (<84 kg), medium (84–116 kg) and heavy (>116 kg) weight categories. Differences were considered significant when *p*-values were less than 0.05.

3. Results

3.1. *Actual work vs. standardised route*

Table 1 illustrates the difference in z-axis average vibration between the actual work and standardised route. Since the forklift drivers drove 7 out of 8 h during their shift, due to meetings and breaks, the A_w, VDV and S_{ed} data from the actual work and standardised route were normalised to 8 h equivalents. The data show that there is a significant difference in A_w between the 1 h of actual work and the standardised route, with the standardised route having substantially higher A_w exposures. There were no differences in VDV exposures between routes. However, the crest factors, TWA peaks, raw positive and negative peaks and D_k were higher during actual work with many of the differences reaching significance. With regard to exposure limits outlined in ISO 2631-1 and 2631-5 standards, during the actual work, the A_w measurements were below the 0.5 m/s^2 action level for both the mechanical and air ride seats. The VDV measurements were above the 9.1 $m/s^{1.75}$ action level but below the exposure limit (21 $m/s^{1.75}$). Finally, the S_{ed} measurements were above the 0.5 MPa action level but below the 0.8 MPa exposure limit.

3.2. *Floor vs. seat vibration levels*

Table 2 compares the z-axis floor and seat WBV exposures over the standard route using four TWA parameters from ISO 2631-1 (A_w, crest factor, VDV and TWA peak) and impulsive parameters from ISO 2631-5 (D_k) and (S_{ed}) along with two other impulsive parameters (raw (+) peak, raw (–) peak). As can be seen in Table 2, with the exception of crest factor, which is a normalised measure, both seats significantly attenuated

Table 1. Whole body vibration mean ($\pm$SE) seat measures comparing actual work and the standardised route ($n = 12$).

Parameter	Axis	Seat suspension	Actual work	Standardised route	*p*-value
A_w (m/s^2)	Z	Mechanical	0.48 ($\pm$0.07)	0.71 ($\pm$0.10)	0.0006
		Air	0.39 ($\pm$0.07)	0.54 ($\pm$0.08)	0.0001
Crest factor	Z	Mechanical	23.8 ($\pm$3.5)	11.2 ($\pm$1.5)	0.004
		Air	32.1 ($\pm$6.3)	14.8 ($\pm$4.9)	0.0001
VDV ($m/s^{1.75}$)	Z	Mechanical	17.6 ($\pm$2.4)	19.0 ($\pm$2.8)	0.35
		Air	13.6 ($\pm$1.6)	12.9 ($\pm$1.6)	0.55
TWA peak (m/s^2)	Z	Mechanical	11.4 ($\pm$1.9)	8.0 ($\pm$1.0)	0.10
		Air	11.2 ($\pm$1.7)	7.0 ($\pm$1.5)	0.02
Raw (+) peak (m/s^2)	Z	Mechanical	31.0 ($\pm$7.3)	15.7 ($\pm$3.3)	0.09
		Air	34.8 ($\pm$7.4)	21.3 ($\pm$9.3)	0.02
Raw (–) peak (m/s^2)	Z	Mechanical	-33.8 ($\pm$4.8)	-21.7 ($\pm$3.5)	0.02
		Air	-47.8 ($\pm$12.2)	-28.3 ($\pm$12.1)	0.03
D_k (m/s^2)	Z	Mechanical	19.2 ($\pm$5.3)	11.7 ($\pm$1.3)	0.15
		Air - Ride	15.0 ($\pm$2.4)	11.5 ($\pm$1.7)	0.05
S_{ed} (MPa)	All	Mechanical	0.69 ($\pm$0.15)	0.43 ($\pm$0.03)	0.09
		Air	0.53 ($\pm$0.07)	0.47 ($\pm$0.04)	0.29
Speed (km/h)	–	Mechanical	5.63 ($\pm$0.7)	10.0 ($\pm$0.4)	0.05
		Air	5.59 ($\pm$1.0)	10.2 ($\pm$0.3)	0.005

A_w = ; VDV = vibration dose value; TWA = time-weighted average; D_k = average daily dose; S_{ed} = static compressive dose.

the WBV exposures relative to the vibration measured at the floor of the forklift.

3.3. Mechanical vs. air suspension seat

Table 3 compares tri-axial WBV exposures between seats using four TWA parameters from ISO 2631-1 (A_w, crest factor, VDV and TWA peak), two parameters from ISO 2631-5 (D_k and S_{ed}) and two other impulsive vibration measurements (raw (+) peak and raw (–) peak). As can be seen in Table 3, the highest exposures and greatest differences between seats were in the z-axis measurements. With the exception of the crest factor, the z-axis exposures were lower in the air ride seat with significant differences in the A_w ($p = 0.03$) and a near significant difference in

Table 2. Standardised route mean (±SE) whole body vibration measures comparing the floor and seat exposures (n = 12).

Parameter	Axis	Seat suspension	Floor	Seat	*p*-value
A_w (m/s^2)	Z	Mechanical	1.33 (±0.03)	0.71 (±0.10)	0.0002
		Air	1.25 (±0.09)	0.54 (±0.08)	<0.0001
Crest factor	Z	Mechanical	11.2 (±0.6)	11.2 (±1.5)	1.00
		Air	10.3 (±0.7)	14.8 (±4.9)	0.31
VDV (m/s$^{1.75}$)	Z	Mechanical	28.7 (±0.5)	19.0 (±2.8)	0.007
		Air	27.6 (±2.0)	12.9 (±1.6)	0.0003
TWA peak (m/s^2)	Z	Mechanical	15.8 (±0.9)	8.0 (±1.0)	0.0002
		Air	13.1 (±0.8)	7.0 (±1.5)	0.006
Raw (+) peak (m/s^2)	Z	Mechanical	59.3 (±8.5)	15.7 (±3.3)	0.0006
		Air	46.4 (±5.9)	21.3 (±9.3)	0.04
Raw (–) peak (m/s^2)	Z	Mechanical	−76.9 (±13.1)	−21.7 (±3.5)	0.003
		Air	−60.5 (±9.8)	−28.3 (±12.1)	0.09
D_k (m/s^2)	Z	Mechanical	32.7 (±2.6)	11.7 (±1.3)	<0.0001
		Air	27.6 (±1.9)	11.5 (±1.7)	0.0002
S_{ed} (MPa)	All	Mechanical	1.05 (±0.08)	0.43 (±0.03)	<0.0001
		Air	0.88 (±0.06)	0.48 (±0.04)	<0.0001

A_w = average weighted vibration; VDV = vibration dose value; TWA = time-weighted average; D_k = average daily dose; S_{ed} = static compressive dose.

Table 3. Mean (± SE) whole body vibration measures from the standardised route by axis comparing seats (n = 12).

Parameter	Axis	Seat suspension		Difference	*p*-value
		Mechanical	Air		
A_w (m/s^2)	X	0.27 ± 0.01	0.27 ± 0.01	0.002	0.74
	Y	0.31 ± 0.01	0.31 ± 0.02	0.001	0.97
	Z	0.71 ± 0.10	0.54 ± 0.08	−0.17	0.03
Crest factor	X	7.7 ± 0.5	7.1 ± 1.0	−0.6	0.50
	Y	8.1 ± 0.7	8.6 ± 0.4	0.6	0.57
	Z	11.2 ± 1.5	14.8 ± 4.9	3.6	0.47
VDV (m/s$^{1.75}$)	X	5.6 ± 0.2	5.7 ± 0.2	0.1	0.54
	Y	6.5 ± 0.2	6.9 ± 0.4	0.4	0.38
	Z	19.0 ± 2.8	12.9 ± 1.6	−6.1	0.06
TWA peak (m/s^2)	X	2.2 ± 0.2	2.1 ± 0.3	−0.1	0.56
	Y	2.6 ± 0.2	2.9 ± 0.3	0.2	0.58
	Z	8.0 ± 1.0	7.0 ± 1.5	−1.0	0.65
Raw (+) peak (m/s^2)	X	11.4 ± 1.0	10.4 ± 1.6	−1.0	0.58
	Y	12.9 ± 3.3	10.9 ± 0.7	−2.0	0.52
	Z	15.7 ± 3.3	21.3 ± 9.3	5.6	0.62
Raw (–) peak (m/s^2)	X	−13.0 ± 1.6	−10.3 ± 1.0	−2.7	0.24
	Y	−10.3 ± 1.3	−10.2 ± 0.8	−0.1	0.94
	Z	−21.7 ± 3.5	−28.3 ± 12.1	6.6	0.65
D_k (m/s^2)	X	7.7 ± 0.4	7.3 ± 0.4	−0.4	0.29
	Y	9.5 ± 0.4	10.8 ± 0.9	1.3	0.22
	Z	11.7 ± 1.3	11.5 ± 1.7	−0.2	0.93
S_{ed} (MPa)	All	0.43 ± 0.03	0.48 ± 0.04	0.05	0.42
Speed (km/h)	–	10.0 ± 0.4	10.2 ± 0.3	0.2	0.42

A_w = average weighted vibration; VDV = vibration dose value; TWA = time-weighted average; D_k = average daily dose; S_{ed} = static compressive dose.

VDV ($p = 0.06$) exposures. As can be seen in the z-axis measures, both seats had crest factors above 9. When crest factors are above 9, this indicates that the A_w data should be interpreted with caution, and VDV exposures should be evaluated due to the likelihood of impulsive exposures (International Organization for Standardization 1997). The impulsive exposure measures tended to be higher in the air suspension seat.

Table 4. Mean (± SE) seat effective amplitude transmissibility (SEAT) values by seat type over the standardised route (n = 12).

Parameter	Seat suspension	Axis	SEAT (%)	*p*-value
A_w (m/s^2)	Mechanical	Z	54.4 (±8.2)	0.20
	Air		44.7 (±6.1)	
VDV ($m/s^{1.75}$)	Mechanical	Z	66.8 (±10.3)	0.56
	Air		56.0 (±14.3)	
Crest factor	Mechanical	Z	102.0 (±15.1)	0.42
	Air		126.8 (±27.8)	
TWA peak (m/s^2)	Mechanical	Z	52.1 (±7.4)	0.71
	Air		60.6 (±19.6)	
Raw (+) peak (m/s^2)	Mechanical	Z	33.5 (±9.9)	0.55
	Air		48.7 (±19.4)	
Raw (–) peak (m/s^2)	Mechanical	Z	42.4 (±10.4)	0.51
	Air		73.1 (±40.0)	
D_k (m/s^2)	Mechanical	Z	37.1 (±4.6)	0.39
	Air		51.2 (±14.4)	
S_{ed}(MPa)	Mechanical	All	42.4 (±3.7)	0.19
	Air		61.6 (±12.8)	

A_w = average weighted vibration; VDV = vibration dose value; TWA = time-weighted average; D_k = average daily dose; S_{ed} = static compression dose.

Note: Higher values indicate poorer performance in seat attenuation.

Table 4 shows the SEAT values, comparing the mechanical and air suspension seats. For the A_w and VDV, both seats attenuated better than half of the vibration measured at the floor of the forklift. However, there were no significant differences in transmissions between the mechanical and air suspension seats.

3.4. *Effect of driver weight on WBV exposures*

Finally, Table 5 compares the WBV exposure measures by seat type across the light (<84 kg), middle (84–116 kg) and heavy (>116 kg) drivers. As can be seen in the table, there was a difference between seats in how the seats attenuated exposures as a function of body mass. With the mechanical seat, most exposures decreased with increasing body mass. In comparison, there was little or no such trend with the air suspension seat. Focusing on the mechanical seat, the trend across driver weights was similar for A_w, VDV and D_k with lighter drivers receiving higher vibration exposures. In contrast to the mechanical seat, the air suspension seat did a substantially better job attenuating exposures in the lightweight drivers.

4. Discussion

This study demonstrated that relative to the vibrations measured at the floor of the forklift (at the base of the seat), both the mechanical and air suspension seats significantly reduced WBV exposures. However, there were performance differences between seats in the

Table 5. Median (range) whole body vibration measures by seat type and driver weight over the standardised route (n = 12).

Parameter	Axis	Seat suspension	Light (n = 4) < 84 kg	Medium (n = 5) 84–116 kg	Heavy (n = 3) > 116 kg	*p*-value
A_w (m/s^2)	Z	Mechanical	1.11 (0.91–1.59)	0.51 (0.44–0.99)	0.45 (0.43–0.46)	0.02
		Air	0.57 (0.47–1.48)	0.47 (0.28–0.53)	0.51 (0.43–0.58)	0.38
Crest factor	Z	Mechanical	8.6 (7.1–10.8)	15.1 (5.0–23.5)	8.6 (7.6–9.7)	0.30
		Air	8.0 (6.5–9.8)	10.3 (5.5–64.3)	6.2 (5.6–25)	0.88
VDV ($m/s^{1.75}$)	Z	Mechanical	29.6 (27.0–37.0)	14.9 (8.0–25.9)	9.0 (8.3–10.6)	0.02
		Air	11.5 (9.4–30.1)	9.7 (8.4–17.8)	10.6 (9.1–15.4)	0.78
TWA peak (m/s^2)	Z	Mechanical	9.7 (9.5–11.3)	10.6 (2.2–12.7)	3.8 (3.2–4.5)	0.15
		Air	5.0 (3.4–10.8)	4.9 (2.5–18.1)	3.2 (2.4–14.4)	0.71
Raw (+) peak (m/s^2)	Z	Mechanical	23.4 (11.5–40.1)	11.0 (3.7–17.8)	5.7 (4.6–20.4)	0.23
		Air	8.1 (4.3–12.4)	22.9 (5.0–117.8)	4.5 (2.8–25.6)	0.23
Raw (–) peak (m/s^2)	Z	Mechanical	–26.6 (–48.8 to –22.6)	–17.3 (–33.4 to –3.7)	–17.0 (–22.0 to –3.6)	0.07
		Air	–15.0 (–18.5 to –6.6)	–27.1 (–150.0 to –3.8)	–5.1 (–27.6 to –2.9)	0.66
D_k (m/s^2)	Z	Mechanical	16.8 (12.5–20.5)	9.5 (7.3–17.0)	7.7 (7.1–8.4)	0.03
		Air	9.7 (7.1–25.6)	8.6 (6.6–20.6)	8.4 (8.3–12.5)	0.99
S_{ed} (MPa)	All	Mechanical	0.54 (0.41–0.66)	0.40 (0.37–0.55)	0.33 (0.30–0.36)	0.02
		Air	0.39 (0.36–0.84)	0.54 (0.35–0.66)	0.39 (0.38–0.48)	0.91
Speed (km/h)*	–	Mechanical	8.6 (6.6–10.5)	10.6 (9.5–11.2)	10.5 (9.7–10.9)	0.52
		Air	9.1 (9.0–9.1)	10.7 (9.8–11.1)	11.0 (11.0–11.0)	0.15

A_w = average weighted vibration; VDV = vibration dose value; TWA = time-weighted average; D_k = average daily dose; S_{ed} = static compressive dose.

*The speed measurements are based on (n = 10) and (n = 7) for the mechanical and air suspension respectively due to a hardware malfunction during the measurements.

attenuation of the WBV exposures. With regard to the low frequency TWA vibration measures, the air suspension seat performed better at attenuating WBV exposures. The air suspension seat had significantly lower z-axis A_w exposures and, although not significant, lower z-axis VDV and TWA-peak exposures. There were no significant differences between seats in attenuating the higher frequency impulsive exposures. In general, the air suspension seat had marginally higher impulsive exposures. Finally, none of the differences between seats in x- and y-axis WBV exposures reached significance, nor were there any systematic trends between seats in the x and y-axis exposures.

4.1. *Actual work vs. standard route*

As illustrated in Table 1, there was a significant difference in A_w exposures between the actual work and standardised route measurements, with the standardised route having higher A_w exposures. This result shows that the constant motion associated with the standardised route results in higher vibration exposures relative to actual work when forklift operators are periodically idle, waiting for their next assignment from the central dispatch office. There were no differences in VDV exposures between routes; however, the crest factors, TWA peaks, raw (+) peaks and raw (–) peaks were higher during actual work, with many of the differences reaching significance. This indicates that the standard route is likely to underestimate peak exposures since there are greater opportunities for peaks during actual work due to the greater distance travelled and longer data collection period.

4.2. *Floor vs. seat*

In all WBV parameters the seat significantly attenuated the vibration relative to the WBV exposures measured at the floor of the forklift (base of the seat). This result suggests that the design of the seat is such that it does not amplify WBV exposure. In some cases, the suspension of a seat can actually amplify the exposure (Paddan and Griffin 2002). This can either be due to the seat being under-damped or the seat oscillating with the resonant frequency of the vehicle.

4.3. *Mechanical vs. air suspension*

In the forklift used in this study, the mechanical seat did not perform as well as the air suspension seat in attenuating the TWA WBV exposures. There were no significant differences between the seats in attenuating the higher frequency impulsive exposures. In general, the air suspension seat had marginally higher impulsive exposures. If these results are generalisable to other forklifts and other mechanical and air suspension seats, the results indicate that an effective engineering control to reduce low frequency WBV exposures is purchasing forklifts with air suspension seats or replacing mechanical suspension seats in existing forklifts with air suspension seats. The air suspension seat tested in this study was more expensive than the mechanical suspension seat (by approximately 250USD). However, this incremental cost is small if spread over the operational life of the vehicle and is certainly small relative to the average cost of a work-related low back injury.

4.4. *Driver weight*

One of the interesting findings was that there were differences between seats in how they attenuated the exposures in the light (<84 kg), middle (84–116 kg) and heavy (> 116 kg) drivers. In the mechanical seat, WBV exposures appeared to be weight-dependent with WBV exposure decreasing as driver weight increased. With the air suspension seat, the same weight-dependent trends were not present and the air suspension seat had universally lower WBV exposures in the lightest-weight drivers. In this study, it appears that lighter forklift drivers may receive higher vibration doses and therefore seat selection is paramount for these lighter drivers.

In conclusion, under the standardised conditions evaluated in this study, the results indicate that both types of seats substantially attenuated forklift WBV exposures. However, the air suspension seats attenuated low frequency WBV exposures more relative to their less expensive mechanical suspension counterparts.

5. Limitations

One limitation was that there were only 12 subjects included in this study due to dropouts and technical difficulties experienced in the data collection process. Given the small sample size in this study, in future studies it would be interesting to determine whether the observed differences between seat types and driver weights apply to other brands of seats and other types of vehicles. In future studies, it would be beneficial to include a variety of seat manufacturers, models and vehicles in order to more broadly quantify the WBV exposure associated with different mechanical and air suspension seats.

A second limitation was that the two seats being compared in this study had different suspension travel distances, with the mechanical seat allowing 20 mm of vertical travel whereas the air suspension seat had 30 mm of vertical travel. The impact of this difference on the results is unknown; however, these were the stock seats sold by the manufacturer and represented the actual procurement choice that would be faced by the vehicle manufacturer or end user. This difference in suspension travel was the only difference in the two seats as they were nearly identical by every other measure.

A third limitation is that there may be some measurement errors in the floor vibration data due to not having any anti-aliasing filtering. Power spectral densities from the seat-mounted accelerometers indicated that the majority of the frequency content was below 30 Hz and virtually no frequency content above 110 Hz. With the floor-mounted accelerometers, the majority of the frequency content was below 80 Hz, with very little frequency content above 275 Hz. These results indicate that it was unlikely that any aliasing would occur in the seat-mounted accelerometers; any aliasing, if present in the floor-mounted accelerometers, was likely to be small.

A final methodological issue that should be pointed out is that the WBV exposures from the 15 min standardised route segments were extrapolated to reflect an 8-h TWA for A_w, VDV and S_{ed}. This extrapolation likely resulted in overestimations of the daily WBV exposures due to the vehicle being in constant motion compared with actual use, where there are likely to be some idle periods. As a result, for accurate WBV exposure dose estimates, actual work measurements of suitable duration should be used to capture actual vehicle operation.

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