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The effect of a multi-axis suspension on whole body vibration exposures and physical stress in the neck and low back in agricultural tractor applications

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ABSTRACT

Whole body vibration (WBV) exposures are often predominant in the fore-aft (x) or lateral (y) axis among off-road agricultural vehicles. However, as the current industry standard seats are designed to reduce mainly vertical (z) axis WBV exposures, they may be less effective in reducing drivers' exposure to multi-axial WBV. Therefore, this laboratory-based study aimed to determine the differences between a single-axial (vertical) and multi-axial (vertical + lateral) suspension seat in reducing WBV exposures, head acceleration, self-reported discomfort, and muscle activity (electromyography) of the major muscle of the low back, neck and shoulders. The results showed that the multi-axial suspension seat had significantly lower WBV exposures compared to the single-axial suspension seats ($p' < 0.04$). Similarly, the multi-axial suspension seat had lower head acceleration and muscle activity of the neck, shoulder, and low back compared to the single-axial suspension seat; some but not all of the differences were statistically significant. These results indicate that the multi-axial suspension seat may reduce the lateral WBV exposures and associated muscular loading in the neck and low back in agricultural vehicle operators.

1. Introduction

Professional vehicle operators suffer from a high prevalence of work-related musculoskeletal disorders (WMSDs) (Rauser et al., 2008; Rauser and Williams, 2014; Kim et al., 2016). Among WMSDs, low back pain (LBP) is the most prevalent (Kim et al., 2016) and the most common worker's compensation claim (Rauser et al., 2008, Rauser and Williams, 2014; Punnett et al., 2005). Whole body vibration (WBV) is a known leading risk factor for LBP among professional vehicle operators (Troup, 1988; NIOSH, 1997; Bovenzi and Hulshof, 1999; Teschke et al., 1999; Burstrom et al., 2015). Biomechanical and biological research has found that exposure to WBV can elevate spinal load (Fritz, 1997, 2000), cause muscle fatigue in the supporting musculature (Wilder et al., 1996), and is linked to the degeneration of the intervertebral discs and subsequent herniations (Seidel et al., 1986; Wilder et al., 1996).

In general, as off-road vehicles including agricultural, construction, military, and mining heavy equipment vehicles are operated on rough terrain, and these vehicle operators are exposed to higher levels of WBV (Lines et al., 1995; Kumar, 2004; Scarlett et al., 2007; Mayton et al., 2008; Smets et al., 2010). Furthermore, while WBV exposures in on-road vehicles are predominantly in the vertical (z) axis, in off-road vehicles, the predominant WBV exposure axis is not necessarily limited to the vertical (z-axis) but can be either fore-aft (x-axis) or lateral (y-axis) (Johnson et al., 2015). Because of the substantial mass of the torso and head, such multi-axial components of WBV exposures can substantially increase the shear and rotational forces in the spine and associated muscle loads to counterbalance the inertia of the torso and head. The long periods of operating off-road vehicles can result in the overuse and damage to the soft tissues in the low back and neck regions, which is a known precursor of musculoskeletal injuries (Rempel et al., 1992; Takala, 2002; Dennerlein et al., 2003; Thomsen et al., 2007). Therefore, off-road vehicle operators may be at greater risk for low back and neck injuries compared to on-road drivers.

Despite the multi-axial nature of the WBV exposure in the operation of off-road vehicles, the current seats on most off-road vehicles are equipped with a single-axial (vertical) industry-standard passive suspension system. Therefore, the current industry-standard seats do not address non-vertical components of WBV exposures, which are often predominant in off-road vehicle operation. This may explain the high prevalence and incidence rates (up to 13 times higher compared to administrative workers) of low back disorders among off-road vehicle operators (Marin et al. 2017). The fore-aft (x-axis) component of WBV

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in off-road vehicles is also a concern (Langer et al., 2015); however, the fore-aft component is predominant primarily in slower moving vehicles which involve a fair deal of stopping/starting, moving forward/backward, and pulling equipment (Langer et al., 2015; Marin et al. 2017). Because these vehicles with for-aft predominant WBV exposures account for a small fraction among all the off-road equipment vehicles, the focus in this study was more on the lateral components of WBV exposures.

Recently, multi-axial suspension seats have been developed to address the limitations of the single-axial seat suspension systems by attenuating both the vertical and lateral component of WBV exposures. However, the efficacy on reducing multi-axial components of the WBW exposures and associated muscle loading on neck and low back muscle has not been systematically evaluated. Therefore, the aim of this study was to determine the potential differences in common WBV exposure metrics in all three dimensions (x, y and z axes) between a single-axial (vertical) and multi-axial (vertical + lateral) suspension seat and differences muscle activity (electromyography: EMG) of major muscles of the neck and low back.

2. Method

2.1. Subjects

In a repeated-measures design, a total of 11 professional truck or agricultural tractor drivers (9 males and 2 females) participated in this laboratory-based study. All the subjects were experienced truck or tractor operators with no pre-existing musculoskeletal disorders in the upper extremities and low back. The subjects' average (± SD) age and driving experience was 47.5 (± 10.9) and 24.9 (± 13.0) years, respectively. Their average (± SD) height, weight, and body mass index were 180.1 (± 7.8) cm, 105.8 (± 28.0) kg, and 32.5 (± 8.1). The experimental protocol was approved by the University's Human Subjects Committee and all subjects provided their written consent prior to their participation in the study.

2.2. Experiment apparatus

2.2.1. Whole body vibration simulation

A six-degree-of-freedom (6-DOF) motion platform (MB-E-6DPF, Moog Inc., East Aurora, NY) played back field-measured vibration profiles from an agricultural tractor. The 6-DOF motion platform consisted of 6 electric linear servo actuators and has been used in previous laboratory-based studies (e.g. Rahmatalla et al., 2008; Blood et al., 2015).

The floor acceleration was collected at 400 Hz using 6-DOF inertial measurement unit (ADIS 16405; Analog Devices; Norwood, MA) mounted on the floor of a large-scale agricultural tractor from six different conditions (Table 1). This 6-DOF sensor consists of a tri-axial accelerometer, a tri-axial gyroscope, and a tri-axial magnetometer. Using the 6-DOF sensor, we were able to replicate more realistic vibration exposure as it enabled us to replay not only linear acceleration but also angular acceleration (roll, pitch, and yaw) with the motion platform. The floor-measured acceleration and angular rates were then filtered by with high pass brickwall filter (discrete Fourier transform, zero low frequency components, and then inverse discrete Fourier transform, and converted to displacement data by simple piecewise integration). The cut off frequency varied from 0 to 0.5 Hz, depending on content in the road profiles. This iterative filtering process continued until the displacement was reduced sufficiently to the limits of the motion platform (an average RMS error of ~10%). The RMS errors were mostly due to high frequency contents (> 30 Hz) which have limited health effects. The displacement data was imported (Replication software; Moog Inc.; Aurora, NY) to reproduce the same (translational + angular) accelerations on the motion platform.

Table 1
The order and duration of six simulated vibration profiles (24 min total).

Order	Description	Duration (Sec)	Proportion (%)
1	Smooth paved road	144	10
2	Representative field work 1	432	30
3	Extreme off-road test track	144	10
4	Representative field work 2	432	30
5	Smooth gravel road	144	10
6	Secondary paved road	144	10
	Total Time	1440	

The 24-min field-measured vibration profile used in this study consisted of data collected from an agricultural tractor traversing six road segments including smooth paved roads, gravel road, farm fields, and extreme off-road terrain (Table 1). The order and duration of each road segments were the same for each seat. The order of the segments reflects the expected WBV exposures commonly experienced by agricultural tractor drivers. To replicate a realistic driving posture during the 24-min vibration exposures, subjects were asked to hold a tractor control joystick mounted on the right side of seat with their right hand, a common controller for heavy-duty agricultural vehicles (Fig. 1).

2.2.2. Seats evaluated

The seat tested in this study was a semi-active suspension seat (MSG 95 EAC/741; Grammer Seating; Hudson, WI). This seat is equipped with a pneumatic semi-active suspension (vertical z-axis) and mechanical spring-based passive suspension (lateral, y-axis). To evaluate the efficacy of lateral (y-axis) suspension, maximize blinding effect and minimize any confounding associated with seat design and, the same seat was used for both experimental conditions by disabling (single-axial: vertical suspension only) and enabling lateral mechanical passive suspension (multi-axial: vertical + lateral suspension). The order of the seat conditions was randomized to minimize potential systematic bias due to the seat order.

2.2.3. Whole body vibration exposures

A tri-axial seat-pad accelerometer (Model 356B40; PCB Piezotronics; Depew, NY) mounted on the driver's seat measured the WBV exposure according to International Organization for Standardization (ISO) 2631-1 whole body vibration standards (Fig. 1). An identical tri-axial accelerometer magnetically mounted to the floor measured the floor vibrations. An additional tri-axial accelerometer rigidly coupled to the subjects' head using a securely fastened headband measured head accelerations. Raw un-weighted acceleration data were simultaneously collected on floor, seat, and head at 1280 Hz using two eight-channel data recorders (Model DA-40; Rion Co. LTD; Tokyo, Japan). The subjects' WBV exposures and seat performance were based on the composite vibration results, taking the average of the seven vibration profiles.

A custom-built LabVIEW program (v2012; National Instruments; Austin, TX) calculated the WBV exposure parameters per ISO 2631-1 and 2631-5 standards as follows:

2.2.3.1. ISO 2631-1 parameters.

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

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

where$a_w(t)$:instantaneous freuquency-weighted acceleration at time,t;T:the duration of the measurement, in seconds.

- Vibration dose value (VDV), which is more sensitive to impulsive vibration and reflects the total, as opposed to average vibration,

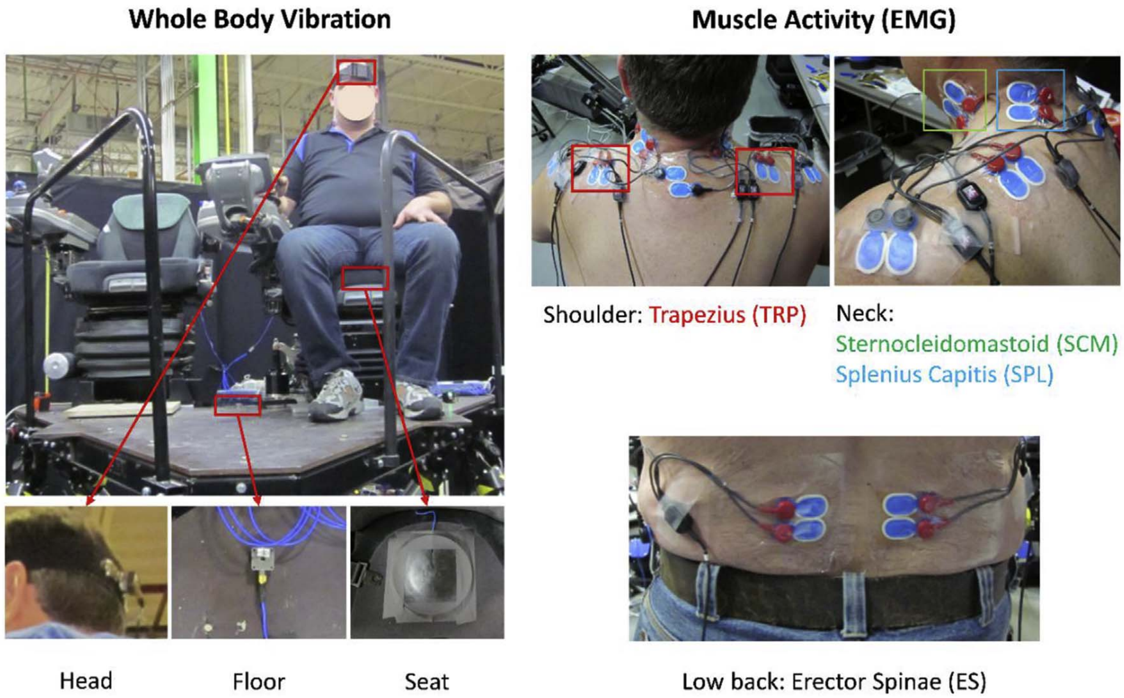

Fig. 1. A subject sitting on the test seat on the vibrating platform (top left). The placements of tri-axial (seat, floor, and head) accelerometers (left) and Ag/AgCl surface shoulder, neck, and low back surface electrodes mounting (right).

over the measurement period at the seat pan and floor of the motion platform ($m/s^{1.75}$):

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

- Maximum transient vibration value (MTVV), the highest 1-s average of the frequency-weighted acceleration, $a_w(t_0)$ during the measurement period (T) based on a 1 s moving window with no overlap between subsequent sample windows:

$$MTVV = \max[a_w(t_0)] \tag{3}$$

2.2.3.2. ISO 2631-5 parameters.

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

$$D_k = \left[\sum_{k=x,y,z} A_{ik}^6\right]^{\frac{1}{6}} \tag{4}$$

whereA_{ik}:the ith Peak of the response acceleration($a_{ik}(t)$);k:*x,y, or z*.

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

$$D_{kd} = D_k\left(\frac{t_d}{t_m}\right)^{\frac{1}{6}} \tag{5}$$

whereD_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}) is a vector sum in mega pascals (MPa):

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

whereD_{kd}:average daily dose vaule in equation in (5)$m_x = 0.015$ MPa/$(m/s^2)$$m_x = 0.032$ MPa/$(m/s^2)$$m_x = 0.015$ 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 exposure to WBV (e.g. $A(8)$, $VDV(8)$, and $S_{ed}(8)$).

As shown in equation (7), the seat effective amplitude transmissibility (SEAT) values were calculated for $A(8)$ and $VDV(8)$ in order to determine how well the seats attenuated the vibration measured at the floor (van Niekerk et al., 2003). Overall seat-to-head transmissibility was also calculated in a similar way to the SEAT value calculation shown in equation (7): a ratio of head acceleration to seat acceleration but does not include output power spectra.

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

Finally, times to reach the EU (European Union) daily action values for A(8) ($0.5\ m/s^2$) and VDV(8) ($9.1\ m/s^{1.75}$) were calculated using the following formulas:

$$T[A(8)] = 8\ hours \times \left[\frac{0.5\ m/s^2}{A(8)}\right]^2 \tag{8}$$

$$T[VDV(8)] = 8\ hours \times \left[\frac{9.1\ m/s^{1.75}}{VDV(8)}\right]^4 \tag{9}$$

2.2.4. Electromyography data collection

Electromyography (EMG) was bilaterally collected from erector spinae (ES), trapezius (TRAP), sternocleidomastoid (SCM) and splenius capitis (SPL) muscle using a data logger with a hardware pre-amplifier bandpass filter of 15–500 Hz (Mega ME6000; Mega Electronics; Kupio, Finland) and Ag/AgCl, surface electrodes (Blue Sensor N; Ambu; Ballerup, Denmark), and sampling at a rate of 1000 Hz during the entire experiment session (Fig. 1). The skin preparation, muscle identification and electrode placement were performed according to the European Recommendation for Surface Electromyography (Hermens et al., 1999).

After collecting the raw EMG data, a band pass filter of 20–400 Hz was applied in the software. This bandwidth was chosen in order to minimize the motion artifacts from the WBV exposures (De Luca et al., 2010). The filtered EMG data were normalized as a percentage of the Maximum Voluntary Contraction (%MVC) for SCM, SPL and TRAP muscles and the sub-maximal Reference Voluntary Contraction (%RVC) for ES muscles. The RVC was chosen to reduce a risk of injuries as the low back is more susceptible to injuries. The MVCs from SCM and SPL were collected during the maximal flexion/extension, bilateral bending and axial rotation (Almosnino et al., 2009). TRAP MVCs were obtained using the methods prescribed by Schuldt and Harmsringdahl (Schuldt and Harmsringdahl, 1988; HarmsRingdahl et al., 1996). ES RVCs were obtained during 30° truck forward flexion. Subjects were asked to practice their MVCs before the actual measurement. Each contraction time lasted for 3 s (Soderberg and Knutson, 2000) with a 2-min break between contractions. Three MVCs were collected from each muscle; the maximum of the highest RMS signal over a 1-s period was identified and used to normalize the EMG data. After normalizing filtered EMG data by either MVC or RVC, the 10th $^{\%tile}$ (static), 50th $^{\%tile}$ (median) and 90th $^{\%tile}$ (peak) amplitude probability density function (APDF) muscle activities were calculated (Jonsson, 1982).

2.2.5. Self-reported discomfort

A Borg CR-10 scale (Borg, 1982) was used to evaluate self-reported discomfort in neck, shoulders, thoracic (mid back), low back, gluteal and legs before and after each experimental condition.

2.3. Statistical analysis

Normality of the data was first evaluated using goodness-of-fit tests. As parametric models are preferred to non-parametric models in order to avoid loss of information, normally or log-normally distributed data were analyzed using mixed linear models. Otherwise, non-parametric tests (Wilcoxon signed-rank tests) were used to analyze the data. Given the non-normality of WBV and muscle activity (EMG) data, *Wilcoxon signed-rank* tests (JMP Ver. 11 Pro, SAS Institute; Cary, SC) was used to determine whether there were differences in WBV exposures and EMG between the single-axial and multi-axial suspension seats. These differences in WBV and EMG were further examined by calculating non-parametric effect size measures, *Hogdes-Lehman* estimators with 95% confidence intervals (Lehmann, 2006; Nussbaum, 2015). The Hodges-Lehman effect size test differently than classical effect size tests in that it is used for estimating the magnitude of differences between two sets of data and the effect size is the median difference between the two groups. Because self-reported discomfort was log-normally distributed, the discomfort data was transformed using natural logarithm. Then, mixed linear model was used to determine whether the changes in self-reported discomfort between pre- and post-exposure differed between the single- and multi-axial suspension seats. Per statistical guidelines for health science journals (Altman et al., 1983), non-normal data were summarized with median and interquartile ranges. The differences in self-reported discomfort were evaluated by a parametric effect size, Cohen's *d* (Cohen, 1988). Statistical significance was noted when p-values were less than 0.05.

3. Results

3.1. Whole body vibration

WBV data, which was a composite average of the six vibration profiles, showed that the WBV exposures were predominantly in the y (lateral) axis (Fig. 2). With identical tri-axial floor inputs created by the simulator, the predominant y-axis A(8) values (Median [25th, 75th]) measured from both single-axial (0.81 [0.48, 0.93] m/s^2) and multi-axial suspension seats (0.70 [0.41, 0.83] m/s^2) were above the EU daily action limits (0.5 m/s^2). Similarly, the predominant y-axis VDV(8) values measured from both single-axial (15.5 [8.7, 18.5] $m/s^{1.75}$) and multi-axial seats (13.5 [7.4, 16.4] $m/s^{1.75}$) were above the EU daily action limits (9.1 $m/s^{1.75}$). The $S_{ed}(8)$ values on the single-axial suspension seat (0.51 [0.30, 0.56] MPa) was above 0.50 MPa, indicating a high probability of an adverse health effect; however, the multi-axial suspension seat (0.40 [0.23, 0.45] MPa) was below 0.50 MPa.

The comparisons of A(8), VDV(8) and $S_{ed}(8)$ WBV exposures between the seats in Fig. 2 showed that the single-axial suspension seat had higher exposures compared to the multi-axial suspension seat ($p = 0.02$, 0.04, and 0.01, respectively). The effect sizes (*Hodges-Lehmann* estimators) indicated that the multi-axial suspension seat has relatively larger effects along lateral (y) axis compared to fore-aft (x) and vertical (z) axis (Table 2).

The seat-measured fore-aft (x) and lateral (y) components of WBV exposures were significantly higher compared to the floor-measured WBV (p's < 0.0001) whereas the seat-measured vertical (z) WBV exposures were lower than the corresponding floor-measured values (p's < 0.0001) (Fig. 2). The Seat Effective Amplitude Transmission (SEAT) values showed that x-axis SEAT values for single- and multi-axial suspension seats were 1.66 and 1.59, respectively ($p = 0.82$), indicating that both seats amplified the fore/aft (x) component of WBV. No differences in magnitude of x-axis amplification were found between the seats. The effect sizes (*Hodges-Lehmann* estimator) on y-axis SEAT values showed that the single-axial suspension seat had significantly higher amplification (1.78) than the multi-axial suspension seats (1.53) ($p < 0.0001$) as shown in Table 2. The z-axis SEAT values for both seats were 0.79 ($p = 0.50$).

The vehicle operating time to reach the EU daily action limits based on predominant y-axis A(8) WBV exposures showed that tractor operators with the multi-axial suspension seat could operate their tractors approximately 1 h longer than those with the single-axial suspension seat (4.1 h vs. 3 h). The time to reach daily action limits based on VDV (8) exposures showed that drivers with the multi-axial suspension seat could operate their tractors approximately 42 min longer than those with the single-axial suspension seat (1.7 h vs. 1.0 h).

3.2. Head acceleration

The root mean square of the weighted head acceleration data showed that the lateral (y-axis) head accelerations were higher than fore-aft (x-axis) accelerations and the vertical (z-axis) head accelerations were similar (Fig. 3). While there are no standards on how to report vibration at the head for sitting subjects, we chose the same weightings as the WBV standards to be able to make similar comparisons. The effect sizes (*Hodges-Lehmann* estimator) indicated that head accelerations were not different between the seats in any directions (Table 2). Seat-to-Head transmissibility (ratios of head acceleration to seat acceleration) showed that the fore-aft (x-axis) and lateral (y-axis) head accelerations were approximately 2.3 (x-axis) and 2.5 (y-axis) times higher than the corresponding acceleration measured at the seats. Although the lateral (y-axis) head accelerations were slightly lower on the multi-axial suspension seat compared to the single-axial suspension seat, the difference was not significant ($p = 0.77$). Furthermore, the effect size (*Hodges-Lehmann* estimator) indicated that the seats had limited effect on reducing the head acceleration in any directions (Table 2). The vertical (z-axis) seat-to-head transmissibility showed that the vertical head acceleration was approximately 1.5 times higher compared to the acceleration measured on both seats.

3.3. Electromyography (EMG)

There was a trend towards a difference in low back muscle activity between the seats (p's $= 0.10$); however, the small, non-significant effect sizes indicted that these differences were rather small (Table 3). Despite the lack of statistical significance and small effect sizes, the left ES muscle activity was approximately 40–60% lower on the multi-axial suspension seat compared to the single-axial suspension seat (Table 3). Although the left ES muscle activity was 44–49% higher than the right

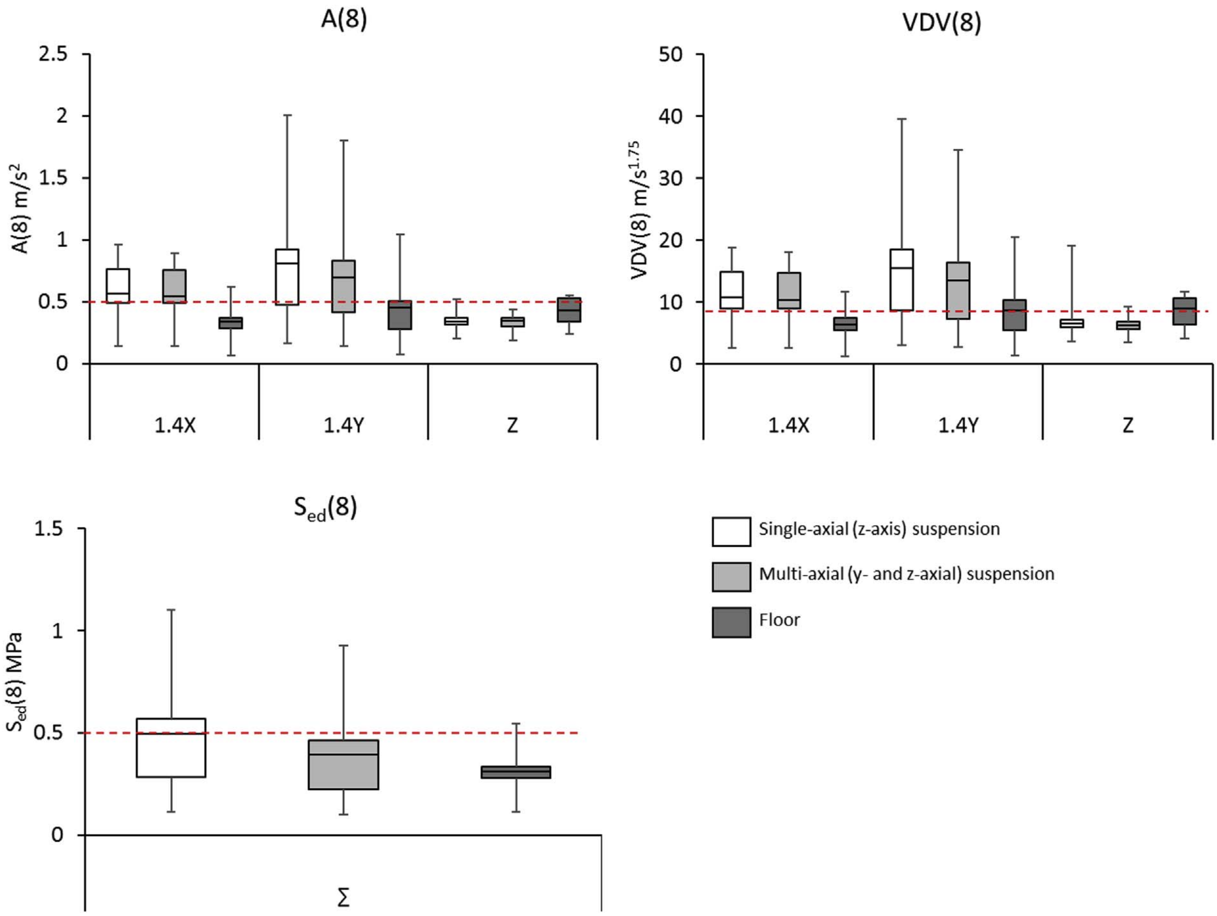

Fig. 2. Average of the six whole-body vibration exposure profiles during simulated agricultural tractor operation: the 8-h equivalent time weighted average vibration (A(8)), vibration dose value (VDV(8)), and daily static compression dose ($S_{ed}(8)$). Σ for $S_{ed}(8)$ indicates the vector sum of all three axes. The boxes indicate interquartile ranges; the horizontal line in the boxes are median values; and whiskers indicate maximum and minimum values. The red dotted lines represent the EU daily action limits for A(8) = 0.50 m/s^2 and VDV(8) = 9.1 $m/s^{1.75}$ and the ISO 2631-5 action limit for $S_{ed}(8)$ = 0.50 MPa [n = 11]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Effect sizes (Hodge-Lehmann estimators) of WBV and Head Acceleration differences between single- and multi-axial suspension seat. The bold numbers show the 95% Confidence Interval (CI) does not include zero, indicating a significant difference.

			Hodges-Lehmann	95% CI	p-value
WBV	A(8)	X	0.01	[-0.03, 0.05]	0.78
		Y	0.09	**[0.02, 0.15]**	**0.02**
		Z	0.00	[-0.01, 0.02]	0.54
	VDV(8)	X	0.16	[-0.85, 1.27]	0.72
		Y	1.85	**[0.13, 3.35]**	**0.04**
		Z	0.19	[-0.06, 0.48]	0.13
	$S_{ed}(8)$	Σ	0.09	**[0.05, 0.15]**	**0.002**
Head Acceleration		X	0.00	[-0.15, 0.13]	0.91
		Y	0.18	[-0.09, 0.51]	0.20
		Z	0.00	[-0.04, 0.04]	0.96
Transmissibility	Head/Seat	X	−0.04	[-0.21, 0.13]	0.63
		Y	−0.04	[-0.19, 0.11]	0.61
		Z	−0.05	[-0.13, 0.04]	0.28
	Seat/Floor	X	0.00	[-0.08, 0.10]	0.82
		Y	**0.20**	**[0.15, 0.25]**	**< 0.0001**
		Z	0.01	[-0.02, 0.05]	0.50

ES muscle activity on the single-axial suspension seat there were no statistically significant differences in muscle activity between the left and right ES with either seat (p's > 0.51). The SCM muscle activities were generally lower on the multi-axial suspension seat compared to the single-axial suspension seat except the 50th percentile value of the left SCM muscle. Similarly, the left SPL muscle activity was 6–17% lower on the multi-axial suspension seat compared to the single-axial suspension seat. In contrast, 10th and 50th percentile values of the right SLP muscle activity were 52% and 2% higher on the multi-axial suspension seat compared to the single-axial suspension seat; however, these differences were not statistically significant. The TRAP muscle activity was also lower with the multi-axial suspension seat compared to the single-axial suspension seat with different degree of statistical significance (Table 3).

3.4. Self-reported discomfort

There were no differences (p's > 0.12; |Cohen's d| < 0.36) in the baseline (pre-exposure) self-reported discomfort in all the six body regions (Fig. 4). The single-axial suspension seat showed slightly greater, but not statistically significant, discomfort changes in the low (lumbar) and mid back (thoracic) regions (p's > 0.26) compared to the multi-axial suspension seat (p's > 0.88). The effect size also indicated that low back discomfort increase on the single-axial suspension seat was much larger (Cohen's d = -0.69) compared to the multi-axial suspension seat (Cohen's d = -0.29). No significant changes in discomfort were found on the gluteal region and legs for either seat after being exposed to WBV (p's > 0.23; |Cohen's d| < 0.11). The neck and shoulder discomfort significantly increased on the multi-axial suspension seat (p = 0.02 and 0.04) while no statistically significant changes in the neck discomfort were found on the single-axial suspension seat (p = 0.99 and 0.13). However, the effect sizes indicated that the seat had limited effects on neck (|Cohen's d| < 0.25) and shoulder

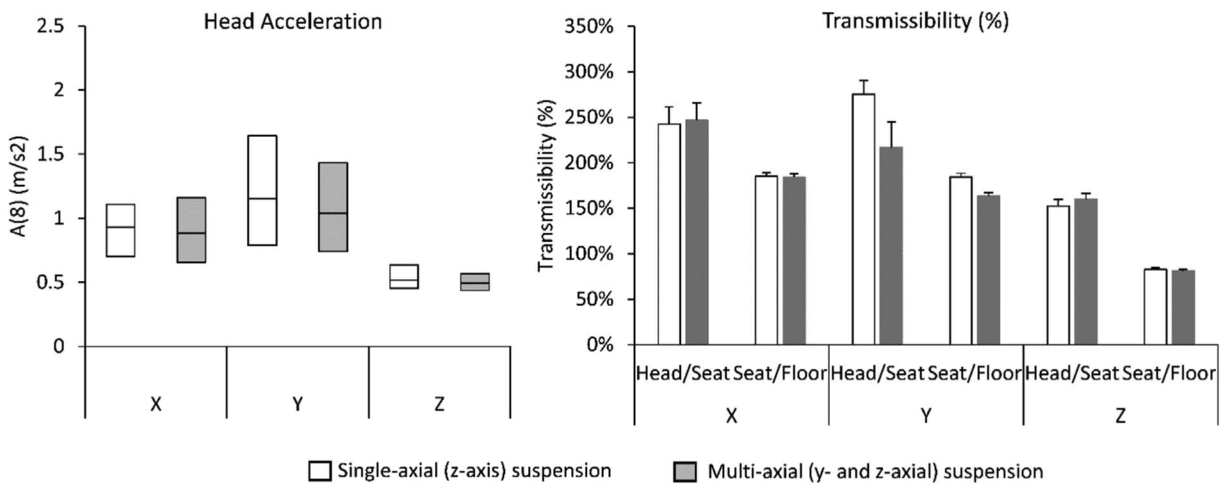

Fig. 3. Head accelerations based on the average of the six agricultural tractor profiles: root mean square head acceleration (m/s^2), seat-to-head (head/seat) and floor-to-seat (seat/floor) transmissibility (%). In the box plots, the boxes indicate interquartile ranges and the horizontal line in the boxes are median values. The bar graph is constructed with means and standard errors [$n = 11$].

discomfort (|Cohen's d| < 0.34).

4. Discussion

This study compared the WBV exposures, neck and low back muscle activity, and self-reported discomfort between single-axial (vertical only) and multi-axial (vertical + lateral) suspension seats while actual field-measured off-road vehicle (agricultural tractor) vibration profiles were reproduced using a large-scale 6-degree-of-freedom motion platform. The results showed that the seat with the multi-axial suspension tended to reduce the WBV exposures and associated muscular loading predominantly in the muscles on the left side during simulated tractor operation.

The results showed that the average of the six WBV exposure profiles collected during agricultural tractor operation and simulated on the vibration platform were predominant on the y (lateral) axis (Fig. 2). This is similar to previous findings that WBV exposures in off-road vehicles including agricultural and mining vehicles are predominantly on the y axis (Scarlett et al., 2007) although some other studies showed that the predominant axis can vary depending on types of vehicle, job, and environment (Mandal & Mansfield, 2016). Because of the substantial mass of the torso and head, the predominant lateral (y-axial) components of WBV exposure can substantially increase muscle loads in the back and neck to counterbalance the inertia of the torso and head (Hinz et al., 2010). Moreover, the lateral accelerations are also associated with discomfort (Beard and Griffin, 2013). Previous studies have examined the effects of fore-aft and lateral vibration on various human responses including subjective discomfort, head acceleration, and visual acuity (Griffin, 1990; Uchikune et al., 1994; Griffin and Brett, 1997; Hirose et al., 2013; Horng et al., 2015). However, there is still a lack of studies that objectively quantify the biomechanical loading on neck and low back. Schust et al. (2015) evaluated internal lumbar load in professional drivers using the finite element model to estimate risks for adverse health outcomes. Their results suggested that fore-aft and lateral vibration could increase shear forces in the spine and therefore contributed to development of adverse health outcomes including low back pain. As the current EU directives and ISO standards focuses on predominant-axis exposures, the current standards may underestimate WBV-related injury risks, especially when there are combined fore-aft and lateral components in WBV exposures (more than one predominant axis).

The results comparing the two seat suspension systems indicate that it may be beneficial for the design of off-road vehicle seats to also address the lateral components of the WBV exposures. Despite no significant difference, the y-axis A(8) and VDV(8) values were approximately 13% lower on the multi-axial (vertical + lateral) suspension seat compared to the single-axial (vertical only) suspension seat indicating there may be a substantial difference in WBV exposures when accumulated over time (a growing season or over years of exposure). Furthermore, as shown in Fig. 3, the SEAT values for A(8) and VDV(8) were significantly lower on the multi-axial suspension seat compared to the single axial suspension seat (p's < 0.0001). This lower lateral WBV exposure on the multi-axial suspension seat were mirrored by lower head acceleration (Fig. 3) and muscle activity (Table 2) compared to the single-axial suspension seat. However, the relatively small effect sizes also indicated that the differences in head acceleration and muscle activity were small; therefore, the current lateral suspension may be further improved to address the lateral component of WBV exposure. This may be due to the fact that the lateral suspension on the multi-axial suspension seat consisted of a simple mechanical spring, which has limited WBV attenuation performance (Blood et al., 2010). These findings may indicate the suspension systems assessed in this study have a marginal benefit and further technological innovation is required.

4.1. Head acceleration

The head acceleration data seat-to-head transmissibility showed that the accelerations were significantly amplified from seat to head in all three axes with greater amplification in the fore-aft (x) and lateral (y) axes (Fig. 3). The amplification at the head level (150 - 280%) was much greater compared to the seat level (seat effective amplitude transmissibility: 79–178%). The greater amplification on x- and y-axis acceleration can significantly increase torque in the neck and associated neck musculature in order to stabilize the head (Hinz et al., 2010); therefore, the neck region may be at greater risk for injury. In addition, this amplified head acceleration may affect visual acuity (Hinz et al., 2010; Horng et al., 2015) which may be an important safety factor for tractor operators.

Although the differences were not significant (small effect sizes), the lateral (x) head acceleration was slightly lower on the multi-axial suspension seat compared to the single-axial suspension seat. This simple spring suspension showed a trend to lower the head accelerator in the lateral (y) direction. Therefore, developing more effective lateral suspension systems that are similar to the current vertical suspension may be beneficial to further reduce risks for the neck injuries and compromised vision by reducing the lateral head acceleration.

Table 3
Median [25th, 75th percentile] normalized muscle activity on erector spinae (%RVC), sternocleidomastoid (%MVC), splenius capitis (%MVC) and trapezius (%MVC). Hodges-Lehmann estimator (95% confidence intervals) are provided as effect size measures [n = 11].

Muscle		Percentile	Seat Suspension		Hodges-Lehmann (95% CI)	p-value[a]
			Single-axial	Multi-axial		
Erector-Spinae (ES)	Right	10th	60.9 [12.6, 233.0]	56.1 [16.6, 339.2]	−0.168 (-0.931, 0.090)	0.21
		50th	71.6 [31.8, 280.4]	74.8 [18.2, 541.9]	−0.145 (-1.266, 0.048)	0.10
		90th	88.3 [48.6, 424.8]	90.2 [38.4, 495.5]	−0.220 (-1.902, 0.057)	0.10
	Left	10th	134.1 [25.6, 242.9]	54.9 [36.9, 128.5]	0.075 (-0.498, 0.723)	0.74
		50th	162.3 [41.4, 285.1]	107.3 [68.1, 460.8]	0.117 (-0.387, 1.030)	0.69
		90th	180.0 [60.7, 333.3]	115.4 [73.6, 229.6]	0.183 (-0.242, 1.097)	0.51
Sternocleido-mastoid (SCM)	Right	10th	3.3 [2.4, 7.6]	3.2 [2.7, 6.1]	0.006 (0.001, 0.020)	**0.02**
		50th	6.1 [4.2, 17.5]	5.5 [3.7, 9.3]	0.014 (0.004, 0.045)	**0.004**
		90th	11.8 [8.4, 24.4]	10.3 [6.7, 16.8]	0.035 (0.008, 0.065)	**0.001**
	Left	10th	2.0 [1.5, 4.2]	1.6 [1.3, 4.1]	0.004 (0.002, 0.007)	**0.001**
		50th	3.4 [2.2, 6.7]	3.9 [1.9, 5.9]	0.005 (0.001, 0.011)	**0.01**
		90th	10.3 [4.7, 19.0]	8.6 [3.9, 19.1]	0.009 (-0.018, 0.046)	0.10
Splenius Capitis (SPL)	Right	10th	17.3 [13.9, 26.8]	26.3 [6.2, 40.9]	0.017 (-0.065, 0.050)	0.55
		50th	37.8 [18.9, 47.1]	38.7 [10.2, 64.4]	0.02 (-0.056, 0.069)	0.32
		90th	65.3 [39.4, 111.7]	57.5 [30.6, 103.1]	0.104 (0.048, 0.237)	**0.001**
	Left	10th	11.1 [4.8, 22.6]	10.5 [4.7, 23.1]	0.009 (0.002, 0.018)	**0.005**
		50th	23.2 [6.8, 43.3]	19.3 [6.7, 44.6]	0.017 (0.004, 0.032)	**0.004**
		90th	37.9 [16.9, 70.0]	34.7 [15.8, 70.9]	0.019 (0.005, 0.065)	**0.02**
Trapezius (TRAP)	Right	10th	1.0 [0.5, 4.1]	1.1 [0.5, 3.3]	0.003 (-0.001, 0.021)	0.13
		50th	2.2 [1.2, 7.8]	1.5 [1.1, 6.1]	0.005 (-0.002, 0.020)	0.10
		90th	11.4 [6.7, 18.6]	8.5 [3.9, 12.4]	0.032 (0.015, 0.050)	**0.002**
	Left	10th	1.5 [0.6, 10.4]	1.2 [0.5, 7.6]	0.004 (0.001, 0.040)	**0.0004**
		50th	2.6 [1.3, 11.6]	1.9 [1.0, 9.5]	0.003 (-0.004, 0.015)	0.08
		90th	10.1 [4.5, 19.7]	6.2 [3.8, 14.8]	0.017 (-0.001, 0.038)	0.06

[a] P-values were calculated using *Wilcoxon signed-rank* tests. Bolded p-values indicate statistical significance ($p < 0.05$).

4.2. Electromyography (EMG)

The EMG data showed a trend that the left ES muscle activity was approximately 40–60% lower on the multi-axial suspension seat compared to the single-axial suspension seat although these differences were not statistically significant (Table 2). The seat-related differences in the right ES muscle activities were smaller. Also, the muscle activity in the right ES was relatively smaller compared to the left ES muscle activity.

The neck muscle activities showed that the multi-axial suspension seat generally had lower SCM muscle activity than the single-axial suspension seat except the 50^{th} percentile value of the left SCM muscle. Similarly, the left SPL muscle activities were 6–17% lower on the multi-axial suspension seat compared to the single-axial suspension seat. The lower muscle activities in the neck and low back muscles mirrored the lower lateral head acceleration on the multi-axial suspension seat, indicating that reducing the lateral WBV exposures may lower neck muscle loadings. However, the small effect sizes indicated that these differences were rather small and that the current lateral mechanical suspension in the multi-axial seat currently has limited effect on reducing muscle loading associated with the lateral components of WBV exposures.

We also observed differences between the left and right sides of the body. Previous studies have shown the differences of left and right ES EMG data especially with the presence of lateral moment (Seroussi and Pope, 1987). The significant lateral component of WBV exposures may have increased lateral moment in the low back and therefore resulted in the differences between left and right ES muscle activities. In addition, this may be due to the fact that subjects held the tractor control joystick mounted on the right side of seat with their right hand, which is a common controller for heavy-duty agricultural vehicles. This asymmetric configuration may have contributed to asymmetrical lateral movements and therefore resulted in muscle activities, especially in erector spinae muscles. When designing controllers for agricultural

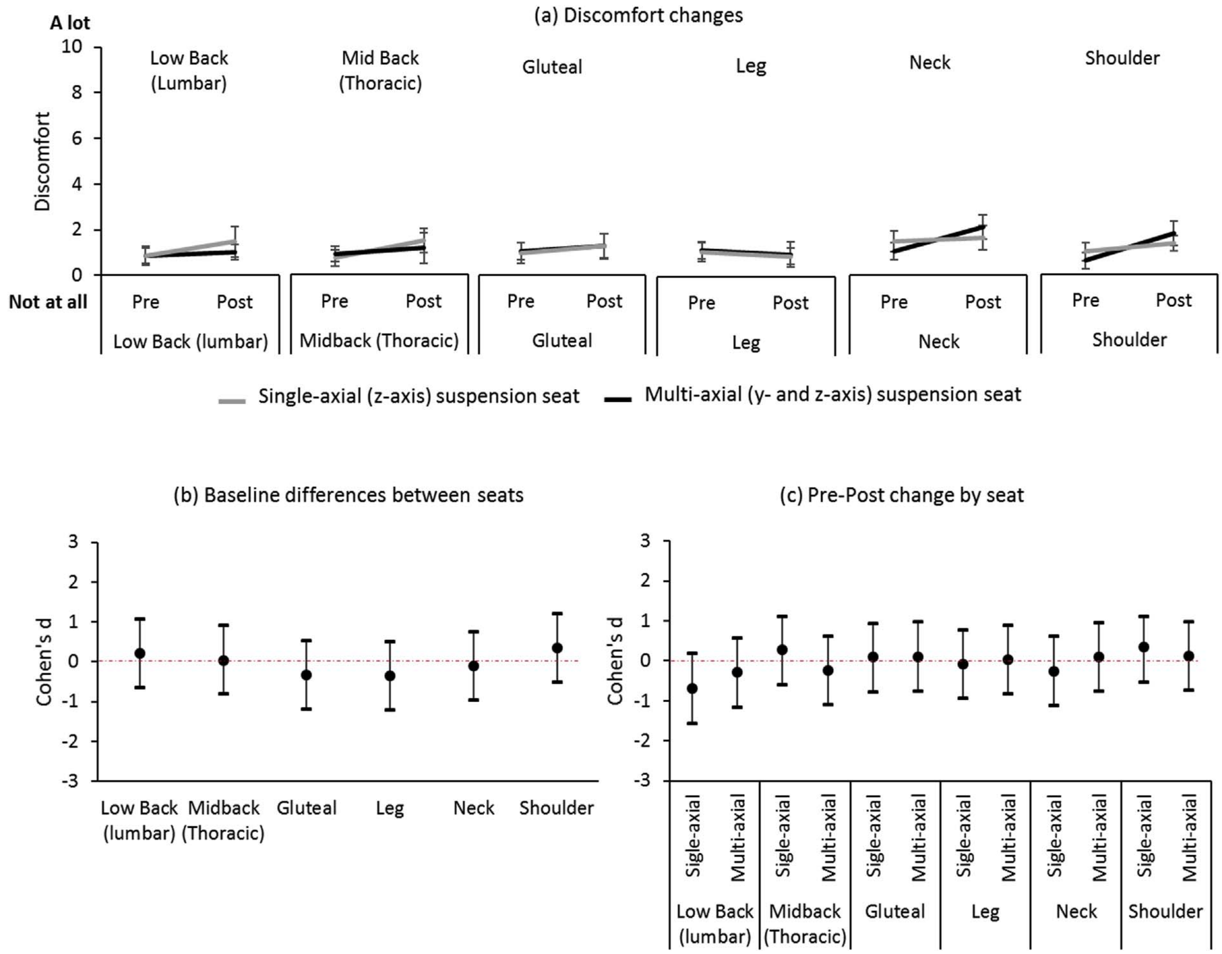

Fig. 4. Self-reported discomfort on six different body parts: (a) changes in mean (SE) discomfort before and after being exposed to WBV on single- and multi-axial suspension seats; (b) Cohen's d (95% confidence intervals) for discomfort differences between the seat before WBV exposures; (c) Cohen's d (95% confidence intervals) for pre- and post-exposure discomfort changes by seat. The red dotted lines indicate no seat effect (b) and no pre-post changes in discomfort. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

vehicles, it may be important to consider symmetrical presentation of controllers that are commonly found in construction heavy equipment such as excavators and bullzoers in order to evenly distribute the musculoskeletal loading between the left and right sides of the body.

4.3. Self-reported discomfort

The results showed a trend that the single-axial suspension seat had slightly greater increases in self-reported discomfort in the low (lumbar) and mid back (thoracic) regions compared to the multi-axial suspension seat (Fig. 4). The greater low back discomfort was in line with the greater erector spinae EMG values on the single-axial suspension seat compared to the multi-axial seat. However, the small effect sizes showed that the changes of discomfort were not significantly different between the seats. The lack of significant difference may have been be due to the short exposure duration (24 min per seat). In contrast, the neck and shoulder discomfort significantly increased on the multi-axial suspension seat while no changes in the neck discomfort were found on the single-axial suspension seat. This is somewhat contradictory to the neck (SCM and SPL) and shoulder (TRAP) muscle EMG. Furthermore, given the relatively short exposure duration and small differences in neck and should EMG between the seats, the self-reported measures may have not been sensitive enough to effectively detect the meaningful differences.

A(8) and VDV(8) values with both seats were above the EU daily action limits and either seat did not significantly reduce the exposures below these limits (A(8) = 0.5 m/s^2; VDV(8) = 9.1 m/s^2) (Fig. 2). These values indicated that tractor operators may experience high levels of exposure to WBV. The S_{ed}(8) value on the single-axial seat was above 0.50 MPa, indicating a higher probability of an adverse health effect (ISO 2631-5). Furthermore, the vehicle operating time to reach the daily action limits indicated that the impulsive VDV(8) exposures were more limiting than the weighted average A(8) exposures due to the reduced tractor operation times. These results support previous findings that tractor operators are likely exposed to high levels of WBV, especially impulsive shocks while operating the vehicles on rough terrain (Mayton et al., 2008). Exposures to these transient shocks that are common in off-road vehicles such as agricultural tractors increase risks of musculoskeletal injuries, especially neck and low back (Bovenzi, 2009, 2010).

4.4. Limitations

Although this study used field-measured vibration profiles to replicate realistic off-road vehicle vibration exposures, the replicated vibration exposures in laboratory settings may be different from real field environments due to many factors including terrain, vehicle types, operation durations and speed. To avoid such biases, the subsets of field-measured vibration profiles were sampled to reflect the realistic distribution of the routes and WBV exposure levels commonly experienced by agricultural tractor operators. Also, the exposure duration of 24 min per seat was relatively short. Therefore, evaluating the seat suspensions during the actual field operation for longer durations may be merited for future studies. Lastly, a sample of eleven subjects may have been an insufficient sample size, which may have resulted in the lack of statistical power and effect sizes, especially for EMG and self-reported discomfort data. Despite these limitations, this study still showed the potential benefit of multi-axial suspension seats for further reducing WBV exposures, head accelerations, and associated muscle loading in the neck and low back.

In conclusion, this laboratory study findings indicate that agricultural tractor operators experience moderate to high exposures to WBV, especially with high impulsive exposures on fore-and-aft and lateral axes. The WBV exposure and EMG data suggest that a lateral suspension, in addition to the vertical suspension, may be more effective in further reducing the WBV exposures and muscular loadings on the neck and low back among the off-road vehicles operators, especially whose WBV exposures are predominantly on y axis.

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