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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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A R T I C L E I N F O

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A B S T R A C T

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):

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

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,