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Original Article

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Whole-Body Vibration and Trunk Posture During Operation of Agricultural Machinery

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Abstract

Exposure to whole-body vibration (WBV) is common among agricultural workers and is associated with musculoskeletal health outcomes such as low back pain. Little is known, however, about the characteristics of exposure experienced during actual production practices. We measured WBV levels during agricultural machinery use among a sample of farmers (n = 55) performing routine agricultural activities and explored machinery attributes that may explain WBV summary measures. We also measured trunk posture to provide additional information about physical exposures during machinery operation. Measurements were made on-farm and during actual work conditions of a sample of agricultural machines (n = 112), including tractors, combines, heavy utility vehicles, and all-terrain vehicles (ATVs). Results indicated the presence of high levels of vibration (median frequency-weighted root-mean-square acceleration of approximately 0.8 m s^{-2}) with time signatures that include high-amplitude mechanical shocks (median crest factor of nearly 23). Compared to other machinery types, combines exhibited the lowest WBV levels and among the most favorable trunk postures. Substantial variability was observed in both the WBV and trunk posture summary measures, suggesting for future studies that alternative sampling strategies are needed to fully capture temporal patterns of machinery use.

Keywords: whole-body vibration; posture; agriculture; musculoskeletal health

Introduction

Agricultural workers experience increased risk of musculoskeletal pain and disorders in comparison to workers in many other industries (Holmberg et al., 2002; Davis and Kotowski, 2007; Kirkhorn et al., 2010; Osborne et al., 2012a). Low back pain (LBP) is particularly common, with an estimated lifetime prevalence of 75% and an estimated 1-year prevalence of 47.8% reported in a recent systematic review (Osborne et al., 2012a), as well as an estimated two-week LBP prevalence of 33.2% observed among farm operators in the Midwest region of the USA (Fethke et al., 2015). The costs associated with the high prevalence of LBP and other low back disorders are disproportionally higher among agricultural workers than workers in other industries (Leigh et al., 2006; Manchikanti et al., 2014).

Exposure to whole-body vibration (WBV) during use of agricultural machinery is a recognized risk factor for LBP (Bovenzi and Betta, 1994; Futatsuka et al., 1998; Toren et al., 2002; Gomez et al., 2003; Mayton et al., 2008; Osborne et al., 2012b). Adoption of non-neutral working postures during operation of agricultural machines may exacerbate risk (Bovenzi and Betta, 1994). With the exception of Zeng et al. (2017a), most previous studies reporting WBV levels during use of agricultural machines in production environments have included small sample sizes and a limited assortment of machine types (Mayton et al., 2008). Thus, it remains unclear how exposure estimates vary among agricultural workers who regularly use different types of machinery. Additionally, few studies have simultaneously assessed trunk posture using direct measurement methods among machinery operators, a potentially important risk factor associated with the development of low back musculoskeletal outcomes (Bovenzi and Betta, 1994; Mayton et al., 2008; Raffler et al., 2017). Of those studies that have (Raffler et al., 2010; Amari et al., 2015; Raffler et al., 2016; Raffler et al., 2017), few measurements from agricultural machines were collected.

This study was conducted to address the aforementioned gaps in the scientific literature by assessing vibration and trunk posture among a sample of farmers in the Midwest region of the USA who used several agricultural machines. Specifically, we sought to (i) characterize WBV exposure during agricultural machinery use among a sample of the farmers performing routine agricultural activities and (ii) explore machinery attributes that may partially explain the high prevalence of LBP among farmers. We expected to observe differences in WBV levels based on the presence or absence of a seat suspension system and based on machine type. We also aimed to characterize the trunk postures adopted during agricultural machine operation.

Methods

Overview and study participants

Participants (n = 55) were a subset of 518 farm operators enrolled in a longitudinal study of physical risk factors and musculoskeletal pain among agricultural workers in the Midwest region of the USA (Fethke et al., 2015). Potentially eligible participants were identified using a random sample of contacts obtained from an agricultural marketing database (Baitinger Consulting, Urbandale, IA). A mailed, self-administered questionnaire was used to recruit participants. Instructions requested that the questionnaire be completed by the person who spends the greatest amount of time engaged in agricultural production. Those responding to the questionnaire were included if the farm operation was active (i.e., produced one or more commodities in the past year). No restrictions for inclusion were made on the basis of demographic, employment (e.g. off-farm employment), or farm operation (e.g. annual sales) characteristics. Enrolled participants self-selected into an on-farm component of the longitudinal study, in which estimates of exposure to physical risk factors (i.e. force, posture, repetition, and WBV) during common agricultural activities were obtained. All study procedures were approved by the University of Iowa Institutional Review Board and written informed consent was obtained prior to participation.

For the 55 participants included in the current study, the mean age was 57.7 ± 9.7 years and the mean body mass index (BMI) was 29.9 ± 5.6 kg m^{-2}. On average, participants reported 37.7 ± 13.3 years of experience working in agriculture. All were Caucasian, two were female, and 36% had obtained a university degree. Farming was reported as the primary occupation for 48 (88%) of the participants. The most common types of operations represented were those producing grain only (e.g. corn and/or soybeans: 26%) and those producing two or more commodities (e.g. grain and beef cattle: 46%).

Data collection strategy

When arranging the on-farm exposure assessment visits, the study coordinator collected information from participants regarding the agricultural activity or activities expected to be performed on the measurement day. For activities involving the operation of self-propelled machinery, our objective was to collect exposure information for the full duration of use or a maximum of four hours.

Machinery characteristics

Vibration and trunk posture measurements were collected during operation of 114 machines. Of these, 65 were classified as tractors, 18 as combines, 15 as heavy utility vehicles (e.g. forklifts and skid loaders), 7 as all-terrain vehicles (ATVs), and 9 as other miscellaneous vehicles (e.g. pick-up trucks and semi-trailer trucks).

The suspension system of each machine seat was visually assessed. When present, suspension systems were typically passive, consisting of a mechanical or air suspension in combination with a hydraulic damper.

Some machines had semi-active or fully active suspension systems. In all cases, controls were available to the operator for adjustment of the suspension characteristics. However, we neither confirmed proper adjustment nor instructed participants to ensure proper adjustment of the systems prior to WBV measurement. Presence of mechanical springs or a seat cushion alone was not considered a suspension system.

Machine age was assessed primarily through participants' self-report of the year of manufacture. Identifying material located on the machine (e.g. serial numbers or engine casting dates) was obtained in some cases. Machine age was then categorized based on year of manufacture as follows: ≤1969, 1970–1989, 1990–1999, and ≥2000.

Instrumentation and summary measures

Whole-body vibration

Vibration was measured at the seat/operator interface according to procedures specified by the International Organization for Standardization (ISO) 2631-1 standard (ISO, 2010). Specifically, a semi-rigid, triaxial seat pad accelerometer (model 356B41; PCB Piezotronics; Depew, NY, USA) was affixed to the seat to register unweighted acceleration in the fore-aft (x-axis), lateral (y axis), and vertical (z-axis) directions. Unweighted vertical acceleration was simultaneously recorded using a single axis accelerometer (model 353B33; PCB Piezotronics; Depew, NY, USA) mounted to the machine floor or frame as near as possible to the midline of the seat base. All raw, unweighted acceleration signals were digitized using a data recorder (DA-20; RION Co., Ltd., Tokyo, Japan) at 1280 Hz per channel. All vibration recordings were processed using custom LabVIEW (National Instruments, Inc., Austin, TX, USA) and MATLAB (The Math Works, Inc., Natick, MA, USA) programs.

Vibration summary measures were calculated using procedures in ISO 2361-1. The frequency-weighted root-mean-square (RMS) acceleration along each axis ($A_{w,axis}$, in m s^{-2}) measured at the seat/operator interface (x-, y-, and z-axes) and at the base of the seat (z-axis only) was calculated as:

$$A_{w,axis} = \left(\frac{1}{T} \int_0^T \left[a_{w,axis}(t) \right]^2 dt \right)^{1/2} \tag{1}$$

where $a_{w,axis}(t)$ is the instantaneous frequency-weighted acceleration at time t and T is the total duration of the measurement. The total frequency-weighted RMS acceleration at the seat of each machine ($A_{w,total}$) was then calculated as:

$$A_{w,total} = \left[(1.4 * A_{w,x})^2 + (1.4 * A_{w,y})^2 + (A_{w,z})^2 \right]^{1/2} \tag{2}$$

Seat effective amplitude transmissibility (SEAT), a unitless metric providing an estimate of the proportion of the frequency-weighted vibration energy transmitted from the base of the seat to the seat/operator interface (Paddan and Griffin, 2002), was calculated as:

$$SEAT = \frac{A_{w,z\ of\ seat}}{A_{w,z\ of\ base}} \tag{3}$$

The vibration crest factor was calculated separately for each axis at the seat/operator interface as the ratio of the maximum absolute value of the instantaneous frequency-weighted acceleration to the frequency-weighted RMS value. The crest factor is a unitless metric.

Finally, the vibration dose value (VDV, in m s$^{-1.75}$) was calculated separately for each axis at the seat/operator interface according to the following formula:

$$VDV_{axis} = \left(\int_0^T \left[a_{w,axis}(t) \right]^4 dt \right)^{1/4} \tag{4}$$

According to ISO 2631-1, VDV provides an estimate of vibration severity for cases in which the crest factor exceeds a value of 9. In contrast to the RMS levels, VDV is cumulative and increases with sampling time.

The European Union (EU) has promulgated a health and safety directive (European Union, 2002) establishing daily WBV 'action values' and 'exposure limits' to which measured frequency-weighted RMS levels (i.e. $A_{w,axis}$) or vibration dose values (i.e. VDV_{axis}) may be compared. Measured $A_{w,axis}$ and VDV_{axis} values were normalized to 8-h equivalent values as follows (Jonsson et al., 2015):

$$A(8) = \max_{axis=x,y,z} \left\{ k * A_{w,axis} * \sqrt{\frac{T_{measured}}{8 hours}} \right\} \tag{5}$$

$$VDV(8) = \max_{axis=x,y,z} \left\{ k * VDV_{axis} * \sqrt[4]{\frac{8 hours}{T_{measured}}} \right\} \tag{6}$$

Note that in Equation 5 the resulting A(8) value will be less than the measured $A_{w,axis}$ value (after factoring the constant k) in cases in which the measurement duration does not exceed eight hours, and is occasionally referred to as the "partial" A(8) exposure value (Zeng et al, 2017a). However, in Equation (6), the resulting VDV(8) value will be greater than the measured VDV_{axis} value (again after factoring the constant k), which reflects the cumulative nature of the VDV metric. We also calculated the time to reach the EU exposure level guidelines given the measured $A_{w,axis}$ and VDV_{axis} values as follows:

$$Time\,to\,A(8) = \min_{axis=x,y,z}\left\{\left(\frac{A(8)}{k * A_{w,axis}}\right)^2 * 8\,hours\right\}$$

Action value	Exposure limit
A(8) = 0.5 ms^{-2}	A(8) = 1.15 ms^{-2}

(7)

$$Time\ to\ VDV = \min_{axis=x,y,z}\left\{\left(\frac{VDV}{k * VDV_{axis}}\right)^4 * T_{measured}\right\}$$

VDV = 9.1 ms$^{-1.75}$ VDV = 21 ms$^{-1.75}$

(8)

As indicated in Equations 5–8 above, the EU directive requires consideration of axis-specific frequency-weighted RMS levels and vibration dose values (where k = 1.4 when $axis = x$ or y and k = 1.0 when $axis = z$).

Trunk posture

Trunk posture was measured simultaneously with WBV using a pair of inertial measurement units (IMUs) (series SXT, Nexgen Ergonomics, Pointe Claire, Quebec). One IMU was secured to the anterior torso just below the sternal notch. The second IMU was secured to the posterior pelvis at the level of the L5/S1 intervertebral disc. The IMU mounting locations and methods were consistent with manufacturer recommendations. Each IMU contained a triaxial accelerometer (±6 g), a triaxial gyroscope (±2000° s^{-1}), and a triaxial magnetometer (±6 Gauss). Raw IMU data were sampled at 20 Hz and stored to onboard memory. The IMUs were calibrated using an "I-pose" reference posture, in which the participant stood with the feet shoulder-width apart and the arms hanging relaxed at the sides.

Trunk angular displacements in the flexion/extension and lateral bending motion planes were estimated based on the relative orientation of the torso and pelvis IMUs using methods described previously (Schall Jr. et al., 2015; Schall Jr et al., 2016; Chen et al., 2018). Briefly, for each IMU, (i) the accelerometer data were used to estimate sensor "pitch" (with respect to gravity) and "roll" (with respect to the horizon) angles on the basis of well-established trigonometric relationships and (ii) the gyroscope data were similarly used to estimate the rates of both pitch and roll. Then, a complementary weighting algorithm was used to combine the accelerometer pitch and gyroscope pitch rate data and the accelerometer roll and gyroscope roll rate data to arrive at sensor-specific estimates of pitch and roll angle:

$$Comp_i = (1-K)\left[Comp_{i-1} + (Rate_i\, x\, dt)\right] + K(Angle_i) \quad (9)$$

where $Comp_i$ is the pitch or roll angle output of the complementary weighting algorithm at sample i, $Comp_{i-1}$ is the pitch or roll angle output of the complementary weighting algorithm at sample $i-1$, $Rate_i$ is the pitch rate or roll rate at sample i, $Angle_i$ is the pitch or roll angle at sample i, and dt is the sampling interval. The constant K defines the relative weighting of the accelerometer (i.e. *Angle*) and gyroscope (i.e. *Rate*) data in the algorithm, and was assigned a value of 0.06 to maintain an overall time constant of 0.77 s, as in Schall Jr et al. (2016). The final flexion/extension angle was defined as the difference in the complementary pitch angles between the torso and pelvis IMUs, and the final lateral bending angle was defined as the difference in the complementary roll angles between the torso and pelvis IMUs.

Summary measures of flexion/extension angle included: the 10th, 50th, and 90th percentiles of the cumulative amplitude distribution, as well as the proportion of measurement time with flexion/extension angles (i) <−15°, (ii) −15° to <15°, and (iii) ≥45°. Summary measures of lateral bending angle included: the 10th, 50th, and 90th percentiles of the cumulative amplitude distribution, as well as the proportion of measurement time with lateral bending angles (i) −15° to <15° and (ii) <−15° or ≥15°. In this study, negative flexion/extension angles denote extension and negative lateral bending angles denote bending to the left.

Data analysis

Vibration measurements from two machines were excluded due to technical failures (one tractor, one heavy utility). Data analyses in this study were primarily exploratory and qualitative, relying on examination of summary measure distributions and overall trends rather than inferential tests. We focused principally on comparing summary measure distributions according to machine type, with median values used to describe central tendency and interquartile ranges (IQR) used to describe variation.

Results

Whole-body vibration during machine operation

Table 1. Distributions of whole-body vibration (WBV) and postural summary measures during use of agricultural machinery; all distributions reported as median (25th percentile, 75th percentile [i.e., interquartile range]).

	All machines	Tractor	Combine	Heavy utility	ATV	Misc.
Number of measures (*N*)	112	64	18	14	7	9
Duration of measure (hours)	0.58 (0.16, 0.87)	0.55 (0.16, 0.82)	1.09 (0.82, 1.54)	0.21 (0.10, 0.52)	0.14 (0.10, 0.58)	0.60 (0.30, 0.79)
WBV summary measures						
Weighted RMS (m s^{-2})						
$A_{w,x}$	0.32 (0.21, 0.42)	0.35 (0.27, 0.44)	0.15 (0.13, 0.19)	0.38 (0.20, 0.52)	0.40 (0.33, 0.48)	0.20 (0.18, 0.24)
$A_{w,y}$	0.32 (0.21, 0.45)	0.37 (0.27, 0.45)	0.15 (0.14, 0.16)	0.35 (0.19, 0.51)	0.46 (0.26, 0.62)	0.26 (0.21, 0.29)
$A_{w,z}$	0.47 (0.32, 0.66)	0.51 (0.38, 0.67)	0.28 (0.24, 0.32)	0.52 (0.39, 0.66)	0.65 (0.43, 0.90)	0.44 (0.41, 0.60)
$A_{w,total}$	0.81 (0.57, 1.07)	0.91 (0.71, 1.15)	0.41 (0.35, 0.48)	0.99 (0.57, 1.24)	1.07 (0.88, 1.39)	0.68 (0.64, 0.87)
A(8) [a]	0.13 (0.08, 0.19)	0.15 (0.09, 0.21)	0.10 (0.08, 0.14)	0.12 (0.07, 0.17)	0.10 (0.06, 0.18)	0.13 (0.10, 0.19)
SEAT	0.70 (0.54, 0.86)	0.77 (0.63, 0.88)	0.50 (0.39, 0.54)	0.73 (0.61, 0.88)	0.73 (0.51, 0.76)	0.73 (0.61, 0.82)
Crest factor (z-axis)	22.91 (13.65, 34.53)	23.99 (16.47, 34.53)	24.16 (12.86, 38.56)	22.45 (12.17, 35.85)	9.78 (6.52, 16.08)	13.81 (12.62, 33.09)
VDV (m $s^{-1.75}$)						
VDV_x	3.11 (2.10, 4.43)	3.40 (2.62, 4.84)	2.12 (1.73, 2.90)	3.66 (2.00, 4.96)	3.60 (2.44, 4.25)	2.75 (1.72, 3.08)
VDV_y	3.12 (2.32, 4.48)	3.73 (2.71, 4.77)	1.87 (1.58, 2.30)	3.19 (1.54, 5.46)	3.01 (1.78, 6.20)	2.86 (2.64, 3.38)
VDV_z	5.80 (4.09, 8.44)	6.23 (4.80, 9.65)	3.87 (3.20, 5.44)	6.91 (3.82, 8.93)	5.36 (3.77, 8.85)	5.94 (5.11, 7.57)
VDV(8) [b]	13.65 (10.48, 18.62)	14.72 (12.45, 19.17)	6.96 (5.69, 8.92)	17.01 (13.13, 22.41)	14.91 (10.64, 23.86)	12.16 (10.58, 14.08)
Postural summary measures						
Flexion/extension angle						
10th percentile (°)	22.6 (10.5, 34.5)	25.3 (13.3, 38.4)	18.4 (10.8, 24.2)	27.2 (16.7, 32.1)	12.7 (−7.6, 27.5)	13.5 (7.9, 21.0)
50th percentile (°)	29.7 (16.3, 43.8)	39.2 (21.9, 47.1)	25.1 (16.1, 33.4)	36.7 (23.8, 42.7)	21.8 (−1.3, 35.1)	19.9 (12.5, 28.0)
90th percentile (°)	37.7 (24.7, 51.2)	44.4 (31.5, 58.1)	32.6 (24.4, 43.5)	45.3 (29.8, 51.2)	34.4 (7.5, 41.9)	25.6 (17.8, 33.3)
<−15° (% time)	0.0 (0.0, 0.0)	0.0 (0.0, 0.0)	0.0 (0.0, 0.0)	0.0 (0.0, 0.0)	0.0 (0.0, 0.9)	0.0 (0.0, 0.0)
−15° to <15° (% time)	2.9 (0.1, 39.7)	1.5 (0.0, 15.5)	6.5 (0.7, 37.1)	1.3 (0.0, 9.4)	24.5 (3.8, 82.1)	37.4 (6.0, 71.8)
≥45° (% time)	2.5 (0.3, 41.8)	18.4 (0.4, 60.1)	0.6 (0.3, 5.2)	11.5 (1.0, 35.4)	1.2 (0.0, 17.4)	0.2 (0.0, 1.7)
Lateral bending angle [c]						
10th percentile (°)	−6.7 (−12.8, −2.3)	−8.4 (−14.1, −3.9)	−4.3 (−9.6, 1.3)	−6.5 (−12.9, −3.3)	−4.0 (−6.1, 1.7)	−8.0 (−9.9, −4.7)
50th percentile (°)	0.2 (−4.4, 3.6)	−1.0 (−4.8, 3.3)	1.7 (−2.4, 5.7)	−1.0 (−2.5, 3.8)	2.4 (0.6, 8.3)	1.4 (−1.4, 2.9)
90th percentile (°)	7.4 (3.2, 11.8)	6.9 (2.2, 12.2)	7.4 (4.6, 10.5)	9.5 (5.1, 12.1)	9.8 (6.1, 14.2)	7.1 (4.7, 8.3)
−15° to <15° (% time)	93.1 (77.5, 97.6)	89.2 (75.5, 97.0)	96.6 (85.1, 99.0)	91.8 (74.5, 95.1)	89.2 (81.3, 97.9)	96.2 (94.5, 98.3)
<−15° or ≥15° (% time)	6.8 (2.4, 22.5)	10.8 (2.7, 24.4)	3.4 (0.9, 14.8)	8.2 (4.9, 25.5)	10.8 (2.0, 18.7)	3.7 (2.0, 5.5)

[a] Maximum axis-specific A(8) according to Equation 5.
[b] Maximum axis-specific VDV(8) according to Equation 6.
[c] Negative values denote lateral bending to the left.

Across all machines, the median $A_{w,total}$ was 0.81 m s^{-2} (IQR: 0.57 to 1.07 m s^{-2}) over a median measurement duration of 0.58 h (IQR: 0.16 to 0.87 h) (Table 1). Median frequency-weighted RMS accelerations were greatest in the vertical direction ($A_{w,z}$) across all machines and for each machine type. The lowest and least variable exposure levels were observed for measurements made during combine operation. The ratio of weighted vertical acceleration at the seat/operator interface to the weighted vertical acceleration at the base of the seat (i.e. SEAT) was also lower and less variable among combines in comparison to other machine types. The median crest factor in the vertical direction across all machines was 22.91 (IQR: 13.65 to 34.53), suggesting the need to consider VDV in the evaluation of exposures. The median VDV_z was 5.80 m s$^{-1.75}$, or approximately 64% of the EU VDV-based action value (9.1 m s$^{-1.75}$).

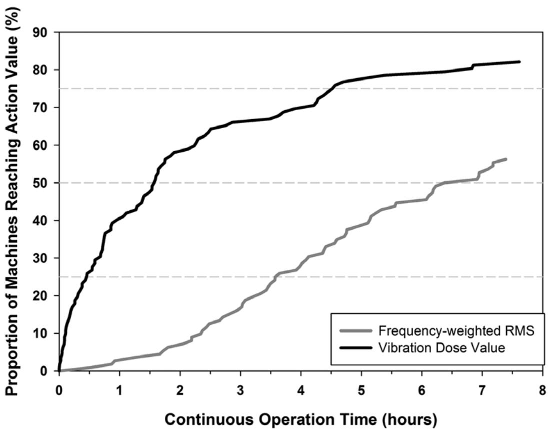

Figure 1. Proportion of machines reaching the EU Action Values for frequency-weighted RMS acceleration and Vibration Dose Value as a function of continuous, uninterrupted operation time; based on calculations in Equations 7 and 8.

Based on the time to EU action value and exposure limit calculations (i.e. Equations 7 and 8), 63 machines (56%) had measured frequency-weighted RMS vibration levels of sufficient magnitude to reach the EU A(8)-based action value (0.5 m s^{-2}) within eight hours of continuous operation (Figure 1). However, as suggested by the high crest factors, 93 machines (83%) had measured VDV levels of sufficient magnitude to reach the EU VDV-based action value (9.1 m s$^{-1.75}$) within eight hours. In fact, the measured VDV levels from 65 machines (58%) were of sufficient magnitude to reach the EU VDV-based action value within two hours. Considering machine type (Table 2), RMS levels from ATVs, heavy utility vehicles,

Table 2. Number (proportion) of machines with measured frequency-weighted RMS and VDV levels of sufficient magnitude to reach the EU action values and exposure limits within different durations of continuous operating time.

	All machines	Tractor	Combine	Heavy utility	ATV	Misc.
Number of measures (*N*)	112	64	18	14	7	9
A(8) action value (0.5 m s^{-2})						
<2 h	7 (6.2)	4 (6.3)	0 (0)	2 (14.3)	0 (0)	1 (11.1)
≥2 to <4 h	24 (21.4)	16 (25.0)	0 (0)	3 (21.4)	4 (57.1)	1 (11.1)
≥4 to <8 h	32 (28.6)	24 (37.5)	0 (0)	4 (28.6)	2 (28.6)	2 (22.2)
Not reached within 8 h	49 (43.8)	20 (31.2)	18 (100)	5 (35.7)	1 (14.3)	5 (55.6)
A(8) exposure limit (1.15 m s^{-2})						
<2 h	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
≥2 to <4 h	1 (0.9)	1 (1.6)	0 (0)	0 (0)	0 (0)	0 (0)
≥4 to <8 h	3 (2.7)	1 (1.6)	0 (0)	1 (7.1)	0 (0)	1 (11.1)
Not reached within 8 h	108 (96.4)	62 (96.9)	18 (100)	13 (92.9)	7 (100)	8 (88.9)
VDV action value (9.1 m s$^{-1.75}$)						
<2 h	65 (58.0)	45 (70.3)	0 (0)	11 (78.6)	5 (71.4)	4 (44.4)
≥2 to <4 h	13 (11.6)	9 (14.1)	1 (5.6)	1 (7.1)	0 (0)	2 (22.2)
≥4 to <8 h	15 (13.4)	6 (9.4)	3 (16.7)	2 (14.3)	2 (28.6)	2 (22.2)
Not reached within 8 h	19 (17.0)	4 (6.3)	14 (77.8)	0 (0)	0 (0)	1 (11.1)
VDV exposure limit (21 m s$^{-1.75}$)						
<2 h	7 (6.3)	5 (7.8)	0 (0)	0 (0)	0 (0)	2 (22.2)
≥2 to <4 h	7 (6.3)	4 (6.3)	0 (0)	2 (14.3)	1 (14.3)	0 (0)
≥4 to <8 h	7 (6.3)	4 (6.3)	0 (0)	2 (14.3)	1 (14.3)	0 (0)
Not reached within 8 h	91 (81.3)	51 (79.7)	18 (100)	10 (71.4)	5 (71.4)	7 (77.8)

and tractors were more likely to reach the action value within eight hours than those from combines and miscellaneous vehicles. The EU exposure limits (A(8) = 1.15 m s^{-2} and VDV = 21 m $s^{-1.75}$) were unlikely to be reached within eight hours regardless of machine type.

Some form of suspension system at the seat was present in about 45% of the machines (Table 3). All combine seats included a suspension system, whereas no heavy utility vehicles (e.g. fork trucks and skid loaders) and less than half of the tractors included such a mechanism (but more frequently among newer tractors). The difference in the SEAT metric between tractors with and without a suspension system was marginal. Furthermore, no clear trends emerged concerning a possible effect of

Table 3. Median (25th percentile, 75th percentile [i.e. interquartile range]) Seat Effective Amplitude Transmissibility (i.e. SEAT) by machine type and according to (i) presence/absence of a seat suspension system and (ii) the year of manufacture of the machine.

	All machines		*Tractor*		*Combine*		*Heavy utility vehicle*	
	N	SEAT	*N*	SEAT	*N*	SEAT	*N*	SEAT
Seat suspension system								
No	60	0.77 (0.63, 0.88)	36	0.77 (0.65, 0.90)	0	—	14	0.73 (0.61, 0.88)
Yes	52	0.60 (0.51, 0.80)	28	0.75 (0.59, 0.87)	18	0.50 (0.39, 0.54)	0	—
Year of manufacture								
≤1969	17	0.79 (0.63, 0.90)	17	0.79 (0.63, 0.90)	0	—	0	—
1970–89	26	0.71 (0.60, 0.88)	21	0.78 (0.63, 0.88)	2	0.49, 0.54 [a]	2	0.58, 0.65 [a]
1990–99	22	0.68 (0.53, 0.82)	14	0.71 (0.58, 0.85)	4	0.56 (0.53, 0.59)	2	0.32, 0.81 [a]
≥2000	39	0.63 (0.49, 0.81)	12	0.75 (0.58, 0.86)	12	0.49 (0.38, 0.53)	7	0.82 (0.68, 0.92)

[a] Actual values of the available observations

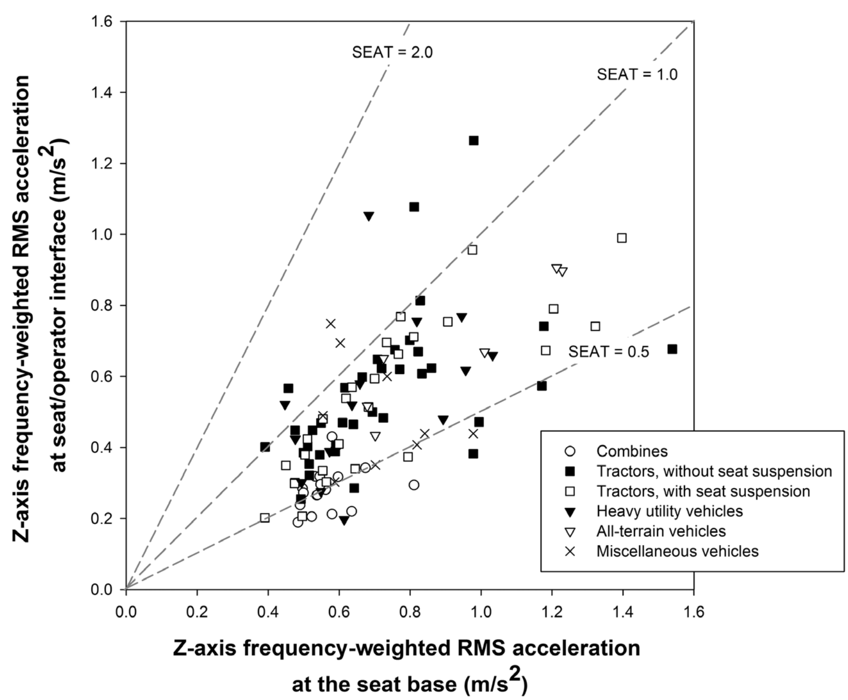

Figure 2. Relationship between measured z-axis frequency-weighted RMS acceleration at the seat base and at the seat/operator interface; SEAT = Seat Effective Amplitude Transmissibility.

machine age on seat performance. However, the attenuation characteristics of the machine seats were relatively consistent across the range of vibration levels measured at the seat base, with the majority of observed SEAT values falling between 0.5 and 1.0 (Figure 2). In addition, although there appeared to be an inverse relationship among tractors between the SEAT value and the operation time required to reach the EU A(8)-based action value, no meaningful difference in the relationship was observed between tractors with and without a seat suspension system (Figure 3).

Trunk posture during machine operation

Across all measurements, the median 50th percentile trunk flexion/extension angle was 29.7° (IQR: 16.3 to 43.8°) while the median 50th percentile lateral bending angle was 0.2° (IQR: −4.4 to 3.6°) (Table 1). Trunk posture summary measure distributions, particularly those describing lateral bending, were characterized by substantial variation. Inspection of the results suggests that operation of combines, ATVs, and miscellaneous vehicles (e.g. pick-up trucks and semi-trailer trucks) was associated with more favorable flexion/extension angle profiles in comparison to tractors and heavy utility vehicles. This is particularly evident when examining the proportion of time with flexion/extension ≥45°, which was, for example, lower and less variable for combines (median: 0.6 %time; IQR: 0.3 to 5.2 %time) than for tractors (median: 18.4 %time; IQR: 0.4 to 60.1 %time). In contrast, lateral bending summary measure distributions were mostly consistent across machine types, although operation of combines and miscellaneous vehicles appeared to result in an increased proportion of time with lateral bending within a "neutral" range (i.e. <−15° to ≤15°).

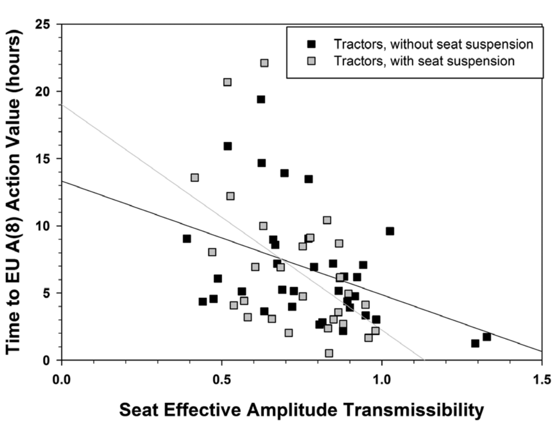

Figure 3. Relationship between Seat Effective Amplitude Transmissibility and time to reach the EU A(8)-based action value for tractors with and without seat suspension systems.

Discussion

Despite consistently observed associations between exposure to WBV and adverse low back outcomes among agricultural workers, little is known about exposure levels experienced during actual production practices. In this study, we captured WBV information from a large number (n = 112) and variety of machines used during production agriculture. Across all measurements, the median frequency-weighted RMS acceleration ($A_{w, total}$) was 0.81 m s^{-2} with a median crest factor (on the z-axis) of about 23. The greatest median $A_{w, total}$ was observed during use of all-terrain vehicles (1.07 m s^{-2}), whereas the lowest median frequency-weighted RMS acceleration was observed during use of combines (0.41 m s^{-2}). Although substantial variation was observed between machine types, these results suggest that, as expected, agricultural machines produce high levels of vibration with time signatures that include high-amplitude mechanical shocks. Consequently, exposure levels were more likely to exceed the VDV-based action value (9.1 m s$^{-1.75}$) than the A(8)-based action value (0.5 m s^{-2}) within 2 h of continuous operating time.

In general, our results are consistent with other field-based studies of WBV during operation of agricultural machines. In a recent study most comparable to ours, Zeng et al. (2017a) reported results of 87 WBV measurements obtained from a variety of agricultural machines, including combines, tractors, and ATVs, among other types. Compared to our study and across all 87 measurements, the $A_{w, total}$ was slightly lower (geometric mean = 0.72 m s^{-2} vs. median = 0.81 m s^{-2}), the crest factor in the vertical direction was somewhat greater (geometric mean = 33.38 vs. median = 22.91), and the VDV in the vertical direction was slightly greater (geometric mean = 7.55 m s$^{-1.75}$ vs. median = 5.80 m s$^{-1.75}$). The mean duration of measurement was somewhat greater in Zeng et al. (2017a), which may partially explain the differences in the observed crest factors and VDV levels. Regardless, the $A_{w, total}$ reported in Zeng et al. (2017a) was also lowest among combines and virtually identical to that observed in our study (geometric mean = 0.46 m s^{-2} vs. median = 0.41 m s^{-2}).

The seats in the current study attenuated between 23 and 50% of the frequency-weighted vertical vibration energy, depending on machine type. The combine seats performed most favorably and most consistently, which is likely due to (i) the greater frequency of more sophisticated semi-active and fully active mechanisms among combines compared to other machines and (ii) the physical and functional similarity of combines between different farm operations. The functional similarity of combines is also highlighted by the reduced variation in $A_{w,total}$ among combine measurements compared to other machines. Somewhat surprisingly, however, we did not observe a meaningful difference in seat performance between machines with and without a seat-based suspension system. Focusing on tractors (n = 36 with and n = 28 without a suspension system), it is possible that the seat suspension systems were (i) not properly adjusted to the weight of the operator and/or (ii) had degraded functionality as a consequence of mechanical wear over time or infiltration of dust (for open-cab machines and/or seats without a dust cowl). Unfortunately, our available data do not support a more detailed investigation of this issue.

Few field-based studies of WBV during use of agricultural machines have examined attenuation of vibration energy through the seat. Paddan and Griffin (2002) observed median SEAT values of 0.85 and 1.07 for samples of seven tractors and three mowers, respectively, across various terrain conditions. However, the measurements were only one minute in duration and, thus, may not be representative of the exposures affecting many agricultural equipment operators. Adam and Jalil (2017) reported a mean SEAT value of 1.13 during operation of a New Holland 55–56 tractor equipped with a suspension system and mowing attachment across tarmac and off-road field conditions. Similar to Paddan and Griffin (2002), however, measurements were only one minute in duration and were obtained from just one participant. The extent of vibration attenuation among the combine seats observed in the current study was similar to that observed among forklifts equipped with an air suspension system (Blood et al., 2010).

Relatively few studies have reported directly measured trunk posture and WBV information simultaneously, and fewer still have involved agricultural machinery in use during actual production. Hermens et al. (2008) used a system of accelerometers, gyroscopes, and electrogoniometers known as CUELA (Ellegast and Kupfer, 2000) and categorized the combined WBV and trunk posture measurements into overall levels of mechanical workload. Specifically, "low" workload was defined as total frequency-weighted RMS acceleration (i.e. $A_{w,total}$) < 0.5 m s^{-2} and forward trunk inclination <60°, and "high" workload was defined as $A_{w,total}$ > 1.5 m s^{-2} (regardless of trunk inclination angle) *or* trunk inclination angle > 60° (regardless of $A_{w,total}$). The methods described by Hermens et al. (2008) have since been used to describe combined WBV and posture data across different machine types (Raffler et al., 2010; Raffler et al., 2016) and to explore within- and between-subject posture variability among operators (Amari et al., 2015). The effects of combined WBV and postural loads on low back outcomes have also been studied (Raffler et al., 2017). Altogether, these studies included a total of less than 100 measurements; only two agricultural tractors were represented (one in Hermens at al. (2008) for a measurement duration < 1 min and one in Raffler et al. (2010) for a measurement duration of about 38 min; neither measurement was obtained in a field setting) although a variety of construction machines were measured.

Raffler et al. (2016) observed median trunk flexion angles of about 10° among a group of bus and locomotive drivers (who primarily drive forward and use a backrest) and 25° among a group of crane and gantry crane operators (who often adopt forward leaning trunk angles while maneuvering the machine both forward and backward). The trunk flexion angles reported in the current study are somewhat greater in magnitude, although the pattern was similar in that vehicles operated predominantly while facing forward (i.e. combines, ATVs, and miscellaneous vehicles) resulted in less trunk flexion than vehicles operated while (on occasion) facing rearward (i.e. tractors and heavy utility vehicles). However, direct comparisons of our results with Raffler et al. (2016) and other studies are limited due to differences in sensor placement and definition of trunk flexion angles.

Axial rotation of the spine, particularly in combination with exposure to WBV, has been associated with increased LBP risk (Wikström, 1993; Hoy et al., 2005; Bovenzi et al., 2006; Eger et al., 2008). Many activities completed by participants in this study that were witnessed by the research team involved axial rotations of the spine during machine operation (e.g. twisting to face rearward and evaluate implements or check harrowing paths). Magnetometer data from the IMUs worn by participants were intended to be used to estimate orientation about gravity and, subsequently, axial rotation angles. However, the magnetometer data collected in this study were deemed unusable for this purpose following inspection of the recorded signals, primarily due to local magnetic field disturbances of unpredictable magnitude and duration. We continue to explore approaches for operationalizing such data in the future.

Several other study limitations should be considered when interpreting the results. Speed and surface condition information was not captured, although WBV levels are likely affected by both (Khorshid et al., 2007; Scarlett et al., 2007). Additionally, no information was collected regarding the lumbar supports included on any of the machine seats. In comparison to a flat backrest, inclusion of a lumbar support has been observed to reduce head motion and perceived discomfort under controlled multi-axis vibration conditions (DeShaw and Rahmatalla, 2016). Other factors, such as horsepower, transmission type, and tire (or tread) configuration, may also partially explain WBV levels (Zeng et al., 2017b).

The times to EU action values and exposure limits were calculated assuming that, for each machine, the measurement duration was sufficient to provide vibration summary measures representative of the true exposure. By definition, VDV will increase as the measurement duration increases. Since it was not always feasible to capture the full duration of machine use during an exposure assessment visit, the VDV levels reported in this study are likely underestimated. In addition, study participants often used more than one machine during a work day, and the temporal patterns of machine use over time are unknown. Zeng et al. (2017a) provided example A(8) levels based on temporal patterns of machine use during a day; however, full characterizations of occupational exposure to WBV among agricultural machine operators will likely require multiple, prolonged measurements to capture the full variation in machine use patterns and vibration levels. Finally, the IMU sensors used in this study were secured to participants using elastic straps that may have moved during the course of data collection. Although the posture estimates were consistent with previous studies, we cannot fully discount the potential contribution of random measurement error to the observed magnitudes of and variability in the postural summary measures.

Conclusions

This study characterized whole-body vibration levels and trunk postures during machine use among farm operators performing routine agricultural activities. Consistent with previous research in this area, results indicated that agricultural machines produce high levels of vibration with time signatures that include high-amplitude mechanical shocks. While the vast majority of machine seats reduced WBV levels to some extent (i.e. SEAT < 1.0), newer machines and/or those with seat-based suspension systems did not appear to produce meaningfully different reductions compared to older machines or those without seat-based suspension systems. Compared to other machinery types, combines exhibited the lowest WBV levels and among the most favorable trunk postures. Substantial variability of both WBV and trunk posture summary measures suggests that sampling strategies designed to more fully capture the temporal patterns of machine use are needed to characterize these exposures in future studies.

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Conflict of Interest

The authors declare no conflicts of interest relating to the material presented in this manuscript. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the CDC or NIOSH.

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