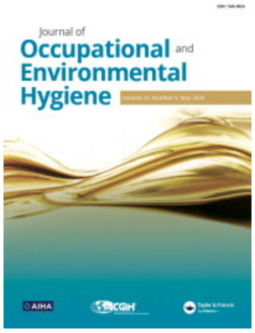

Journal of Occupational and Environmental Hygiene

ISSN: 1545-9624 (Print) 1545-9632 (Online) Journal homepage: www.tandfonline.com/journals/uoeh20

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To cite this article: Brian Fiegel, Yash Kumar Dhabi, Geb Thomas, Salam Rahmatalla, Elizabeth M. Ritchie, Adam Ramker, Oliver Stroh, David G. Wilder & Nathan B. Fethke (29 May 2026): A customized system for whole-body vibration measurement, Journal of Occupational and Environmental Hygiene, DOI: 10.1080/15459624.2026.2659859

To link to this article: https://doi.org/10.1080/15459624.2026.2659859

Published online: 29 May 2026.

JOURNAL OF OCCUPATIONAL AND ENVIRONMENTAL HYGIENE
https://doi.org/10.1080/15459624.2026.2659859

A customized system for whole-body vibration measurement

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ABSTRACT

This manuscript describes the technical components and performance of a custom whole-body vibration (WBV) instrumentation system designed for autonomous, prolonged field measurement. The study demonstrated the technical readiness of the system's accelerometers. The system integrates a Teensy 4.1 microcontroller, triaxial microelectromechanical system accelerometers, force sensing resistors, global positioning system module, and microSD data storage. The accelerometers were validated against reference accelerometers commonly used in field-based WBV measurement using a motion simulator programmed with complex vibration input profiles specified in ISO 7096:2020 *Earth-Moving Machinery—Laboratory Evaluation of Operator Seat Vibration* for testing operator seat vibration in earth moving machinery. In the time domain, accelerometers in the custom WBV instrumentation system exhibited $\leq$ 2.21% error in root-mean-square (RMS) amplitude measurements and $<$ 0.03 g sample-to-sample RMS deviation from the reference accelerometers. Frequency-domain analysis (1/3-octave band) suggested slight underestimation of signal power at low frequencies ($\leq$10 Hz), but the differences were practically small at each 1/3-octave band. Ultimately, the system will enable WBV monitoring in settings in which operators are remote and/or the schedule of machine operation is variable (e.g., agriculture). Future work will focus on real-world validation and exploring use of the force sensing resistors to characterize operator posture, further enhancing the system's utility in occupational WBV exposure monitoring.

KEYWORDS
Exposure assessment; lowcost instrumentation; validation; whole-body vibration

Introduction

Occupational exposure to whole-body vibration (WBV) is a key contributor to the burden of low back problems in many industry settings, with reviews on the topic spanning several decades (Hulshof and Veldhuijzen van Zanten 1987; Bovenzi and Hulshof 1998; Singh et al. 2024). The equipment and procedures used to measure and evaluate WBV exposures are guided by well-established consensus standards, primarily ISO 8041 (ISO 2017), ISO 2631-1 (ISO 2010), and ISO 2631-5 (ISO 2018). The ISO standards also underpin occupational WBV exposure guidelines and regulations worldwide, including the American Conference of Governmental Industrial Hygienists (ACGIH®) Threshold Limit Value for WBV (ACGIH 2025) and the European Union's health and safety directive (European Union 2002).

Despite the availability of ISO standards and WBV exposure guidelines/regulations, substantial knowledge gaps persist in the understanding of the association between WBV and low back problems. For example, risk estimates (e.g., odds ratios, risk ratios, and the like) reported in epidemiologic studies are predominantly based on self-reported information about WBV exposure, frequently with dichotomous (e.g., exposed or not exposed) or ordinal (low, medium, or high exposure) variables (Lings and Leboeuf-Yde 2000; Kwaku Essien et al. 2018; Swain et al. 2020; Jahn et al. 2023). When direct measurement has been used to estimate WBV exposure in an epidemiologic study, sampling strategies have frequently involved single measurements of relatively short duration and/or measurement among a subset of workers (Bovenzi 1996; Lings and Leboeuf-Yde 2000). In some settings, exposure levels both within and between days may not appreciably vary, and so a single, short-duration

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measurement may reasonably represent exposure. However, in some industries, such as agriculture, the within- and between-day variability in work content and environmental conditions can be substantial (Zeng et al. 2017; Fethke et al. 2018). Therefore, a single measurement may not represent all possible WBV exposure conditions, and the accuracy and precision of reported WBV exposure measurements are unclear.

The general absence of published information about the variability of WBV exposure metrics (e.g., frequency-weighted root-mean-square (RMS) amplitude) extends to metrics used to describe the vibration mitigation performance of machine seat suspensions, such as Seat Effective Amplitude Transmissibility (SEAT) (Paddan and Griffin 2002). Manufacturers of agricultural machines typically evaluate SEAT under controlled conditions specified in ISO 5007 *Agricultural Wheeled Tractors—Operator's Seat—Laboratory Measurement of Transmitted Vibration* (ISO 2003). However, laboratory-based SEAT results may not generalize to all operators and all field conditions. In a classic study, Burdorf and Swuste (1993) tested 11 machine seats (including five designed for tractors) in the laboratory and again in the workplace among 24 machines on which existing versions of the tested seats were installed. In the laboratory, SEAT was ~22% greater, on average, for a lighter subject (53 kg) compared to a heavier (93 kg) subject. Furthermore, the tractors seats tested exhibited a SEAT value < 1.0 in the laboratory (average $= 0.68$, or 32% reduction in WBV exposure) but four of the five seats exhibited a SEAT value >1.0 in the workplace (average $= 1.06$, or 6% increase in vibration). From an intervention perspective, large between-day variation of the SEAT value within a particular machine suggests the need for multi-day sampling to achieve statistically stable estimates of the SEAT value. Similarly, large between-operator variation of the SEAT value is undesirable for exposure control at the machine level.

Our broader research goals involve an effort to characterize the variability, as well as the accuracy and precision, of WBV exposure measurements (including SEAT) among agricultural machine operators. Our exposure assessment approach requires the repeated collection of exposure data from a large number of varied machine types (e.g., tractors, combines, and the like) in row crop operations over a full production cycle (i.e., planting through harvest). Commercially available WBV instrumentation systems for use in field settings require researcher intervention to start and stop data collection. Therefore, carrying out a large-scale exposure measurement campaign is logistically challenging (if not outright infeasible) in industries like agriculture, in which workers are geographically dispersed, the schedule of machine operation is variable, and environmental conditions may disrupt scheduled data collection efforts. In such circumstances, instrumentation that offers autonomous data collection is necessary. Furthermore, if the exposure measurement campaign requires the collection of vibration data from numerous machines on the same day (as might happen during the short harvest window), then the total cost of commercially available devices can easily exceed financial resources available.

Alternative approaches to standard, commercially available WBV instrumentation for repeated and/or long-duration exposure assessment have been explored. For example, Olson et al. (2020) used accelerometer data loggers (AX3, Axivity, Hoults, Yard, UK) to sample vibration at the floor and seats of long-haul truck cabs continuously over four days. Acceleration recorded using the AX3 data logger has shown good agreement with standard WBV measurement equipment (Pierson et al. 2021); however, for measurement at the seat/operator interface, the accelerometer should be embedded within a semi-rigid rubber (or plastic) disk that has been designed according to ISO 10326-1 *Mechanical Vibration—Laboratory Method for Evaluating Vehicle Seat Vibration; Part 1: Basic Requirements* (ISO 2016). Indeed, commercially available WBV instrumentation systems include a "seat pad accelerometer" for this purpose (e.g., model 356B41, PCB Piezotronics, Depew, NY, costing ~$1900 US).

Handheld Apple iPod Touch devices have also been used in conjunction with the "WBV" iOS application as an alternative to purpose-built WBV instrumentation systems for repeated and/or long duration measurement (Burgess-Limerick and Lynas 2016; Mayton and Kim 2018; Lynas and Burgess-Limerick 2020). The "WBV" iOS application automatically applies the ISO 2631-1 human vibration weighting filters and calculates related exposure summary metrics including the frequency-weighted RMS amplitude and vibration dose value (VDV), which can benefit practitioner users who may not have access to digital signal processing software. However, Apple iPod devices share the form factor limitation of the AX3 accelerometer data logger. In addition, the maximum accelerometer sampling rate of Apple devices is typically 100 Hz, restricting the frequency content of the recorded signals to 50 Hz and limiting the ability to accurately capture high-frequency events, such as mechanical shocks common in agricultural environments (Roeder et al. 2022).

To support the research goals of the current study and advance the science of WBV exposure assessment, a custom WBV instrumentation system was developed. Key features include: autonomous data collection to minimize logistical challenges to repeated exposure measurement over long time scales, replaceable external sensors, a custom seat pad accelerometer (designed to ISO 10326-1 specifications) with incorporated force sensing resistors to detect the presence of an operator, and a global positioning system (GPS) module for tracking machine location and ground speed. This article presents the technical components of the system and describes the performance of its accelerometers with respect to reference accelerometers with the expectation that the design may be useful to other researchers who need to make WBV measurements not easily facilitated by existing commercial systems.

Methods

System components

The custom WBV instrumentation system (Figure 1) consists of three main components: (i) a seat pad sensor containing a triaxial accelerometer and force sensing resistors to be mounted at the seat/operator interface, (ii) a base sensor containing a triaxial accelerometer to be mounted to the base of the seat suspension system, and (iii) a compute board unit containing a microcontroller, anti-aliasing Butterworth low-pass filters, a triaxial "wake-up" accelerometer, a GPS module, microSD data storage, and other electronics.

Seat pad and base sensors

The seat pad and base sensors each contain a triaxial MEMS accelerometer (ADXL326, Analog Devices, Wilmington, MA). The ADXL326 is a general-purpose accelerometer with a full-scale range of ±16 g and analog output, and is marketed for commercial applications. It is low cost while measuring both static (DC) and dynamic (AC) acceleration. The dynamic acceleration bandwidth is 0.5–1,600 Hz on the X and Y axes and 0.5–550 Hz on the Z axes. Prior to digitization, all accelerometer voltage signals were passed through a low-pass filter (second order, Butterworth, 100 Hz corner frequency), as specified in ISO 8041-1 (ISO 2017). No hardware high-pass filter was used since preserving the DC acceleration was desirable to allow calculation of sensor orientation relative to gravity.

Each ADXL326 was mounted to a custom printed circuit board (PCB). For the seat pad sensor, the PCB was rigidly attached to a thin metal plate (75 mm diameter × 1.5 mm thickness) and secured within a rubber disk designed to meet specifications in ISO 10326 (ISO 2016). Specifically, the diameter of the rubber disk was 250 mm and the rubber material (PMC-790 Industrial Liquid Rubber Compound) measured 87 (± 1) on the Shore A hardness scale. For the base sensor, the PCB was mounted within a 3D-

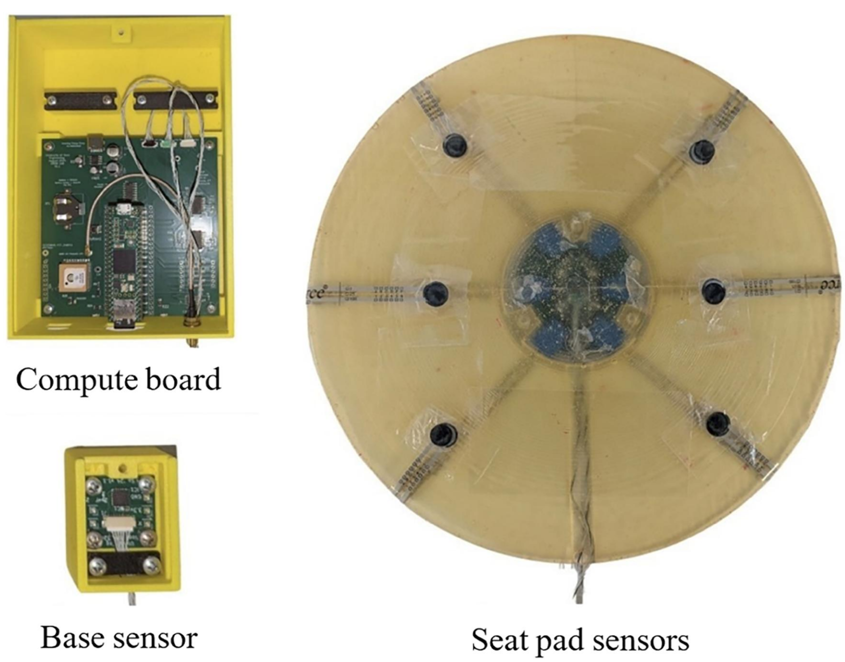

Figure 1. Main components of the custom WBV instrumentation system.

printed (35.4 mm × 27.4 mm) box to be adhered to a structural element of a machine at the base of the seat suspension. The purpose of the dual accelerometer approach (i.e., seat pad and base sensors) was to measure transmissibility of vibration from the base of the seat suspension to the operator (Paddan and Griffin 2002).

On the seat pad sensor, six force sensing resistors (FlexiForce A201, Tekscan, Inc., Norwood, MA) were used to detect the presence of a machine operator. Multiple force sensing resistors were used to ensure adequate signal should the operator change their seated posture in such a way as to fully unload a single sensor. The force sensing resistors were aligned 62.5 mm from the anterior/posterior center line of the rubber disk, typical of the distance between the ischial tuberosities (Sauer et al. 2007).

Compute board

A microcontroller (Teensy 4.1, PJRC.com, Sherwood, OR) sampled analog voltage signals from the seat pad and base sensors using its built-in, 12-bit, analog-to-digital converter (ADC). All seat pad and base sensor accelerometer voltage signals (filtered) were sampled at 500 Hz, and voltage signals from the force sensing resistors were sampled at 5 Hz. A GPS module (PA1616D, CDtop Technology, Kaohsiung, Taiwan) on the compute board was used as means to track machine location and ground speed during machine operation with the GPS antenna placed on an exterior surface of the machine. The Teensy 4.1 recorded GPS data at 1 Hz. All data values were logged to a standard microSD card, and the data files were formatted as comma-separated text files for later processing and analysis.

A low-power, triaxial accelerometer (ADXL362, Analog Devices, Wilmington, MA) located on the compute board was monitored by the Teensy 4.1 to enable system "sleep" and "wake-up" functionality for autonomous data collection. The sleep and wake-up conditions were independently configurable, based on detected acceleration amplitude levels above (or below) a specified threshold for a specified duration.

The compute board included LEDs to indicate power status and alert the user to an error that has disrupted system functions. A push button was also available to allow users to manually initiate data logging.

System power

The system consumed 0.822 W while actively logging data and 0.171 W while in its low-power, inactive mode. On the compute board, a USB-C port was available for connection to an external 5 V DC power source. The power was conditioned for the system on the compute board using an inverting charge pump.

Accelerometer calibration

Static calibration was used to determine the sensitivity of each axis of each accelerometer (ADXL326). Using a mechanical jig, each sensor axis was aligned parallel (+1 g) and antiparallel (−1 g) to gravity. At each orientation, the Teensy 4.1 took 10 ADC readings that were averaged to estimate the digital value (dv). The digital values with the sensor aligned parallel to gravity ($dv_{(+1g)}$) and antiparallel to gravity ($dv_{(-1g)}$) were then used to calculate the digital value when the sensor axis was orthogonal to gravity ($dv_{(0g)}$) and the sensitivity (S_d), as shown in Equations 1 and 2. For any recorded digital value, acceleration (a_g), in units of g, was then calculated according to Equation 3:

$$dv_{(0g)} = \frac{dv_{(+1g)} + dv_{(-1g)}}{2} \tag{1}$$

$$S_d = \frac{dv_{(+1g)} - dv_{(-1g)}}{2} \tag{2}$$

$$a_g = \frac{dv - dv_{(0g)}}{S_d} \tag{3}$$

Accelerometer validation

Experimental procedures

Dynamic acceleration from the ADXL326 accelerometers within the seat pad and base sensors of the custom WBV instrumentation system was compared to that from reference accelerometers (seat pad reference: model 356B41; base reference: model 356A14; PCB Piezotronics, Depew, NY). The custom seat pad and base sensors, along with their reference counterparts (see Table 1 for specification comparison), were glued to the platform of a six-degrees-of-freedom motion simulator (Moog-FCS 628 Ann Arbor, MI) (Figure 2). The reference accelerometers were connected to data acquisition hardware (Krypton 8XACC, DEWEsoft, Whitehouse, OH) and sampled at 500 Hz using DewesoftX (ver. 2023).

The input profiles (z-axis only) used were a selection of those described in ISO 7096 for testing seat vibration in earth-moving machinery (ISO 2020), specifically "EM1" (articulated- or rigid-frame dumper), "EM3" (wheeled loader), "EM6" (crawler dumper), and "EM9" (skid steer loader). The profiles provided

Table 1. Basic specifications for ADXL326, PCB Piezotronics Model 356B41, and PCB Piezotronics Model 356A14.

Specification	Analog Devices ADXL326 *(Custom, Base and Seat Pad)*	PCB 356B41 *(Reference, Seat Pad)*	PCB 356A14 *(Reference, Base)*
Sensitivity*	57 mV/g typical at VS = 3 V (51–63 mV/g), ratiometric	110 mV/g (± 10%)	100 mV/g (± 10%)
Measurement Range	±16 g (typical ±19 g)	±10 g pk	±50 g pk
Frequency Range†	x,y axes: 0.5 to 1,600 Hz z-axis: 0.5 to 550 Hz	0.5 to 1,000 Hz (±5%)	0.5 to 5,000 Hz (±5%)
Resonant Frequency	5.5 kHz	≥ 27 kHz	≥ 25 kHz
Broadband Resolution‡		0.0002 g RMS typical	0.0001 g RMS typical
Noise Density‡	~0.0003 g/√Hz (per axis). RMS depends on bandwidth		
Non-Linearity	±0.3% FS	≤ 1%	≤1%
Overload Limit (Shock)	±10,000 g (powered or unpowered)	±2,000 g pk	±7,000 g pk
Temperature Range	−40 to +185 °F	−10 to 122 °F	−65 to 176 °F
Temperature Response	Sensitivity tempco ±0.01%/°C (~0.0056%/°F); zero-g bias tempco ±1 mg/°C.	< 0.10%/°F	For response curve: https://www.pcb.com/products?m=356a14

*Ratiometric sensitivity (ADXL326): Zero-g bias ≈ VS/2 and mV/g sensitivity scale with supply voltage (VS). If the ADC reference is tied to VS, supply changes cancel in code/"counts per g"; if not, supply variation appears as gain/offset drift.
†For the ADXL326, frequency range is the −3 dB output bandwidth with user-set first-order filters (not flatness bands); for the PCB accelerometers, frequency ranges are specified as ±5% amplitude flatness bands (not −3 dB output bandwidth).
‡The ADXL326 datasheet gives noise density (μg/√Hz); RMS depends on the chosen bandwidth and filter; PCB quotes broadband resolution as integrated RMS noise over a stated band (e.g., 1–10 kHz).

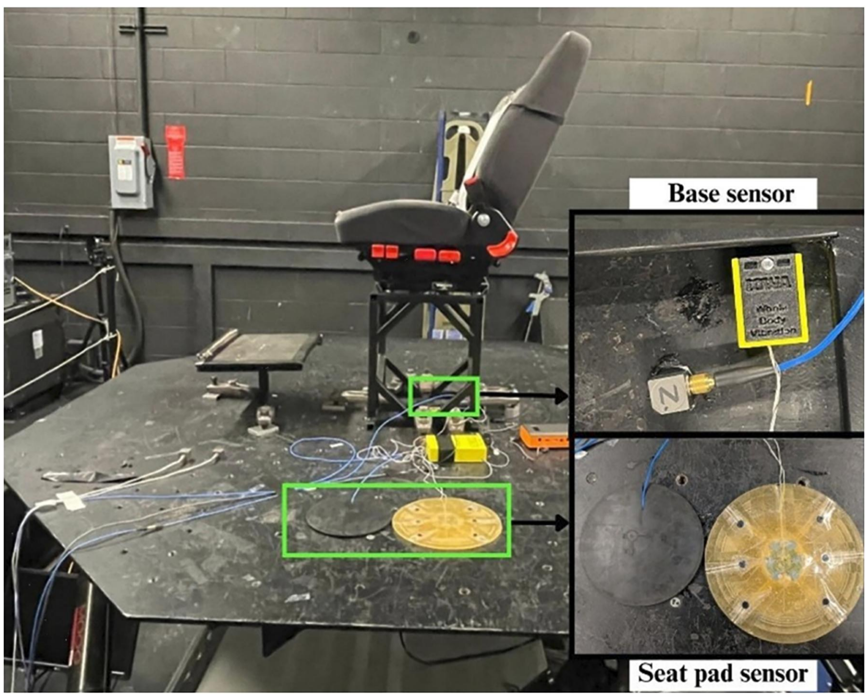

Figure 2. Custom WBV instrumentation system sensors and reference accelerometers attached to motion simulator.

ranges of vibration amplitude and frequency content over which to compare the time and frequency domain information of data obtained from the custom and reference accelerometers (Figure 3). Each input profile was 3 min and was run twice.

Prior to starting each vibration input profile run, data collection was initiated for both the custom WBV instrumentation system and the reference accelerometers, and then the motion simulator platform was struck with a rubber mallet to induce a sharp, distinct acceleration spike in the data from each system.

Accelerometer data processing

Cross-correlation was used to synchronize data from the custom the reference accelerometers (Rhudy 2014). The acceleration spikes from the mallet strikes allowed for visual confirmation of synchronization following the cross-correlation analyses. Mean subtraction was then used to remove the DC offset of each accelerometer signal.

Reference accelerometer data were passed through a zero-phase digital low-pass filter (second order, Butterworth, 100 Hz corner frequency). The design of

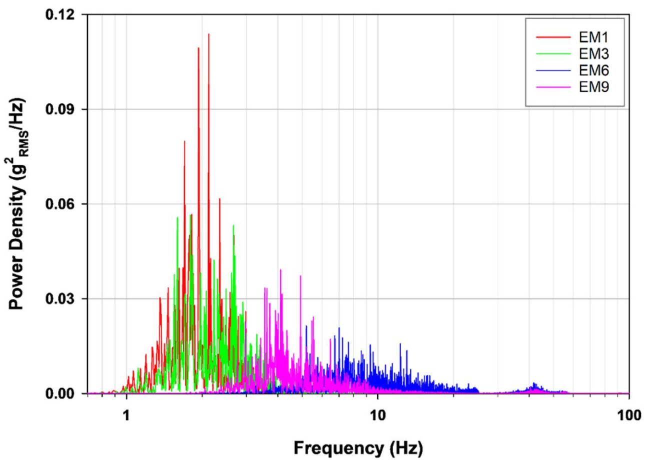

Figure 3. Frequency content of motion simulator input profiles.

the digital low-pass filter for the reference accelerometers matched the design of the hardware low-pass filters used in the custom WBV instrumentation system.

All data processing was performed in MATLAB (version R2023a, MathWorks, Natick, MA).

Time domain analysis

Time-domain features of each accelerometer signal considered for comparison included the minimum, maximum, and RMS amplitudes (all in g). Error was then quantified in two ways: 1) as the percent difference in the RMS amplitude between the custom and reference accelerometers (error, %; Equation 4), and 2) as the sample-to-sample RMS difference between the custom and reference accelerometers (RMSD, g; Equation 5). In Equation 4, RMS_{cust} and RMS_{ref} are the RMS amplitudes measured by the custom and reference accelerometers, respectively, across the duration of the input vibration profile run. In Equation 5, $a_{cust,i}$ is the acceleration measured by the custom accelerometer at sample i, $a_{ref,i}$ is the acceleration measured by reference accelerometer at sample i, and n is the total number of samples recorded during the input vibration profile run:

$$error\ (\%) = \frac{|RMS_{cust} - RMS_{ref}|}{RMS_{ref}} x(100\%) \quad (4)$$

$$RMSD = \sqrt{\sum_{i=1}^{n} \left(a_{cust,i} - a_{ref,i}\right)^2 / n} \quad (5)$$

Frequency domain analysis

Time series data from both the custom and reference accelerometers were transformed to the frequency domain using the standard one-third octave bands specified in ISO 2631-1 (ISO 2010). Comparison of the one-third octave power spectra allowed for an assessment of the agreement between the custom and reference accelerometers across the range of frequencies considered in WBV exposure evaluation.

Results

The waveform patterns from the custom seat pad accelerometer sensor closely followed those of the reference accelerometer, with precise alignment of acceleration peaks and troughs across the full duration of the input vibration profile run (Figure 4). Similar results were observed when comparing the custom base accelerometer to the reference base accelerometer.

Across all input profiles, time series summary metrics from the custom seat pad and base accelerometers closely matched those from the reference accelerometers (Table 2). Differences in acceleration minima and maxima were generally < 0.05 g and differences in RMS levels across the full duration of the input vibration profiles were generally ≤ 0.004 g. Error in RMS levels ranged from 0.06% (EM1, run 1 for the custom base accelerometer) to 2.21% (EM1, run 2 for the custom seat pad accelerometer). Similarly, the sample-to-sample RMSD were low, ranging from 0.011 g (EM9, run 2 for the custom base accelerometer) to 0.028 g (EM1, run 1 for the custom seat pad accelerometer).

The high levels of agreement between both the custom seat pad and base accelerometers and the respective reference accelerometers suggest that materials used in their construction do not introduce unexpected or unacceptable error. However, results indicate that the seat pad accelerometers (both custom and reference) detect slightly lower RMS acceleration levels than the base accelerometers across all input vibration profiles. In addition, the error in both RMS levels and RMSD tended to be greater for the custom seat pad accelerometer than for the custom base accelerometer at each input vibration profile (except for

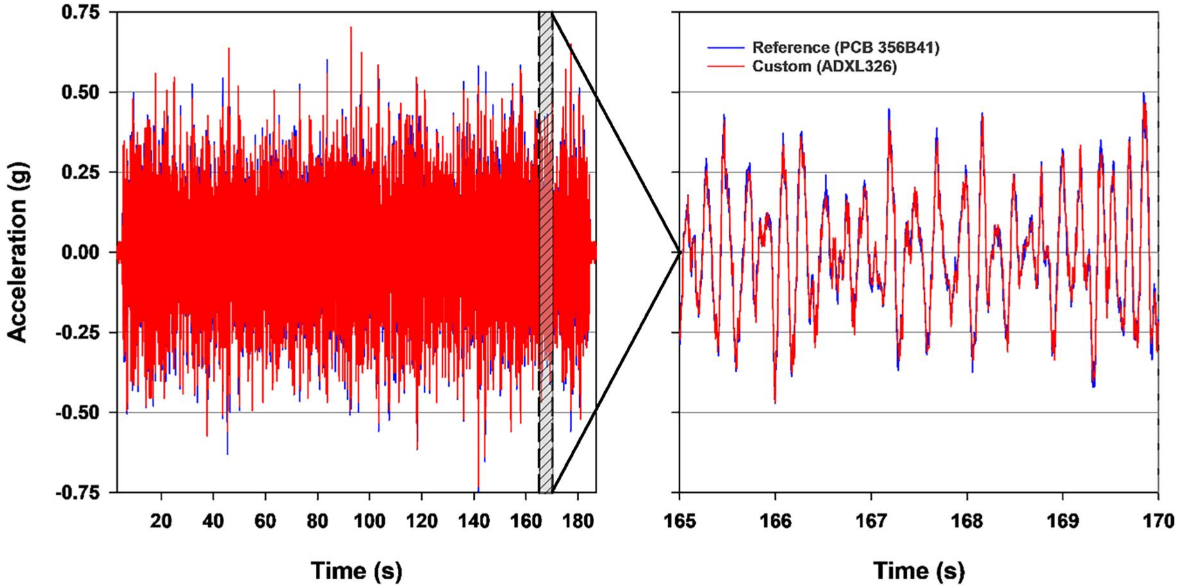

Figure 4. Custom (red) and reference (blue) seat pad accelerometers signals from the EM9 input vibration profile: left = full duration; right = 5-s segment.

Table 2. Time-domain features of the custom ("Cust.") and reference ("Ref.") accelerometer signals by input vibration profile, along with custom accelerometer error metrics.

		Seat Pad Accelerometer				Base Accelerometer			
		Run 1		*Run 2*		*Run 1*		*Run 2*	
Input	Metric	Cust.	Ref.	Cust.	Ref.	Cust.	Ref.	Cust.	Ref.
EM1	Min (g)	−0.669	−0.622	−0.629	−0.640	−0.732	−0.719	−0.693	−0.697
	Max (g)	0.651	0.657	0.641	0.625	0.801	0.784	0.805	0.816
	RMS* (g)	0.170	0.173	0.172	0.176	0.174	0.175	0.176	0.177
	Error† (%)	1.870	–	2.210	–	0.060	–	0.067	–
	RMSD‡ (g)	0.028	–	0.023	–	0.021	–	0.019	–
EM3	Min (g)	−0.632	−0.660	−0.631	−0.653	−0.758	−0.742	−0.780	−0.773
	Max (g)	0.647	0.659	0.633	0.689	0.707	0.717	0.690	0.710
	RMS* (g)	0.157	0.161	0.158	0.161	0.162	0.163	0.162	0.163
	Error† (%)	2.040	–	1.990	–	0.169	–	0.154	–
	RMSD‡ (g)	0.022	–	0.021	–	0.019	–	0.016	–
EM6	Min (g)	−0.692	−0.700	−0.720	−0.702	−0.897	−0.897	−0.885	−0.907
	Max (g)	0.854	0.776	0.805	0.771	0.915	0.919	0.957	0.958
	RMS* (g)	0.176	0.176	0.176	0.175	0.203	0.204	0.202	0.204
	Error† (%)	0.371	–	0.386	–	0.789	–	0.776	–
	RMSD‡ (g)	0.021	–	0.021	–	0.021	–	0.013	–
EM9	Min (g)	−0.752	−0.723	−0.743	−0.732	−0.706	−0.708	−0.806	−0.819
	Max (g)	0.708	0.697	0.680	0.672	0.756	0.747	0.744	0.714
	RMS* (g)	0.167	0.169	0.167	0.169	0.179	0.180	0.179	0.180
	Error† (%)	1.318	–	1.320	–	0.465	–	0.531	–
	RMSD‡ (g)	0.020	–	0.019	–	0.018	–	0.011	–

*RMS = root-mean-square amplitude, calculated across full duration of input vibration profile run.
†Percent error (i.e., from Equation 4).
‡RMSD = sample-to-sample root-mean-square difference (i.e., from Equation 5).

EM6, in which error was greater for the custom base accelerometer).

Inspection of 1/3-octave power spectra suggests that the custom WBV instrumentation system accurately replicates vibration signals across the frequency bandwidth pertinent to ISO 2631-1. An example is provided in Figure 5, in which slight underestimation of power is observed in the 3.15–8.0 Hz bands for the custom seat pad accelerometer compared to its reference accelerometer.

Across all input vibration profiles and data collection runs, mean differences in power of $< 0.0003\,g^2_{RMS}$ were observed between the custom and reference accelerometers at each 1/3-octave frequency band (Figure 6). However, a few differences were apparent in the responses from the custom seat pad

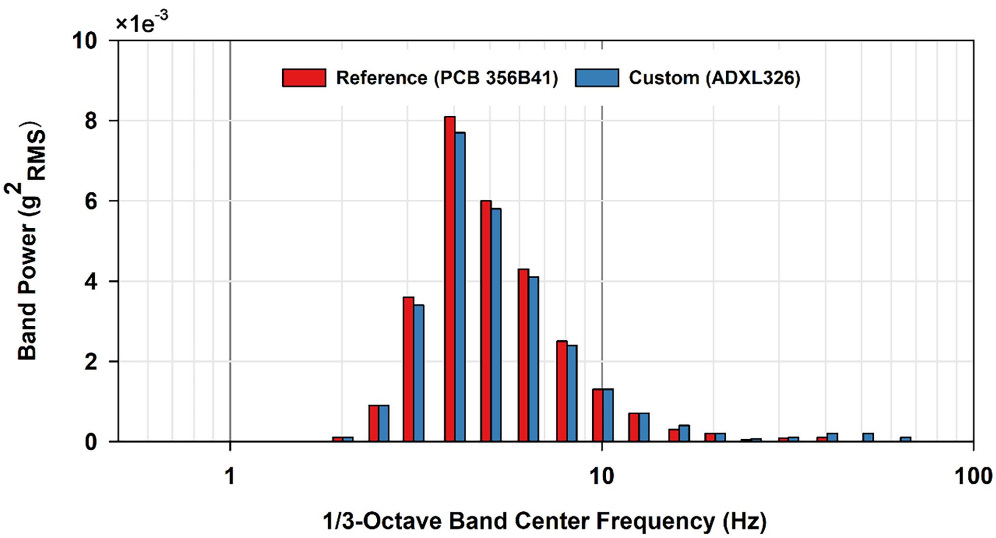

Figure 5. 1/3-octave spectra for the custom seat pad accelerometer (blue) and the reference seat pad accelerometer (red) under EM9.

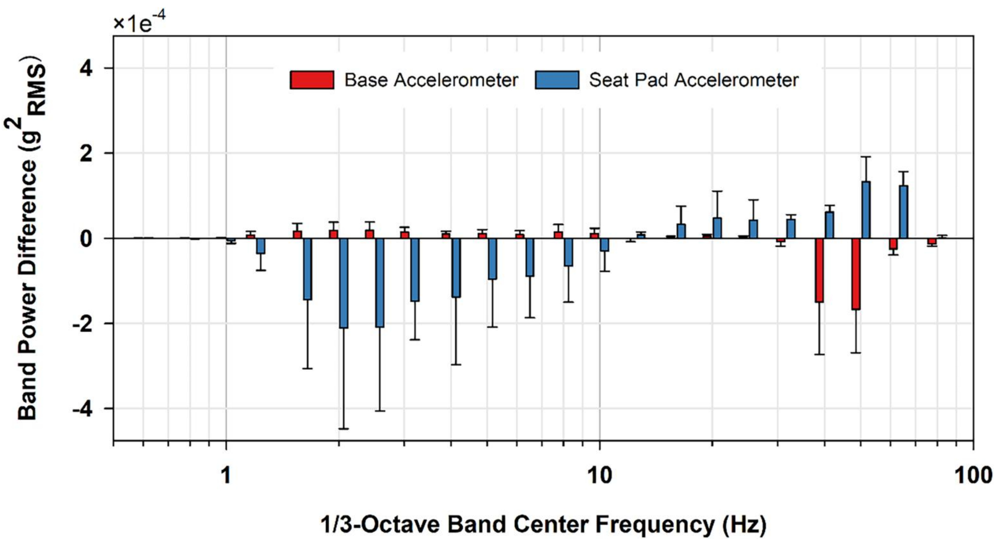

Figure 6. Mean difference in 1/3-octave band power between the custom and reference accelerometers across all input vibration profiles and runs; error bars represent standard deviation.

and base accelerometers. In general, the magnitude of the mean differences in power was lower for the custom base accelerometer than for the custom seat pad accelerometer (except at the 40 Hz and 50 Hz bands). Also, in the lower frequency bands (1.0–10 Hz), the custom seat pad accelerometer tended to underestimate power while the custom base accelerometer exhibited a slight overestimation of power. However, the opposite was observed in the higher frequency bands, particularly > 30 Hz. The differences in response behavior may be attributed to the differences in structural dynamics and material properties of the custom seat pad and base sensors. Regardless, the small magnitude of the power differences ($< 0.0005\ g^2_{RMS}$) with respect to the reference accelerometers is likely of negligible practical relevance.

Discussion

Overall, results suggest that the ADXL326 accelerometers, as configured within the custom WBV instrumentation system, may serve as a suitable substitute for commercially available accelerometers for measuring vibration both at the seat/operator interface and at the base of the seat suspension. Differences between the accelerometers in this system and reference accelerometers used in field-based WBV assessment were practically small, both in the time and frequency domains.

A strength of this approach to accelerometer validation was the use of standard, complex input vibration profiles specified in ISO 7096 (ISO 2020). The profiles allowed for efficient examination of differences between the custom and reference accelerometers across a range of frequencies. By comparison, Pierson et al. (2021) evaluated the performance of the AX3 accelerometer data logger under pure sinusoidal inputs (of varying amplitude and frequency) and under complex vibration inputs obtained from a passenger vehicle traveling over "very rough" and cobblestone road surfaces. Error between the AX3 and a reference accelerometer in the unweighted RMS amplitude was generally $< 1\%$ under sinusoidal vibration, which is slightly lower than error observed in this study under complex vibration for the seat pad sensor. The maximum sinusoidal acceleration amplitude in Pierson et al. (2021) was $5\,\mathrm{m{\cdot}s^{-2}}$, which is somewhat lower than the maxima reported in this study ($\sim$0.6–0.9 g, depending on EM profile and trial). However, Pierson et al. (2021) did not report the frequency distribution of the complex vibration inputs, so it is not possible to compare the performance of the custom WBV instrumentation system to the AX3 accelerometer logger in that respect.

An important observation was the simultaneous underestimation of vibration power by the seat pad sensor and overestimation of power by the base sensor at frequencies up to 10 Hz, in comparison to the respective reference accelerometers. Because measurement of seat suspension transmissibility is a ratio of the frequency-weighted RMS acceleration at the seat/operator interface to the frequency-weighted RMS acceleration at the base of the seat suspension (Paddan and Griffin 2002), the magnitude of the measurement may be lower than the true value (i.e., suggesting better vibration attenuation performance). The underestimation of power by the seat pad sensor was greater than the overestimation of power by the base sensor, so error in transmissibility measurement is likely to be driven by the seat pad sensor. Based on data from this study, potential error in SEAT value is likely to be in the direction of underestimation but practically small ($\sim$2%). In this study, however, the seat pad sensor was tested without the mass of an operator. Therefore, additional testing is needed to confirm whether a similar pattern of over/underestimation is observed in the presence of an operator.

Limitations

The system was tested in a laboratory setting without a human operator. As a result, the effects of body mass, posture, and seat contact on measurement accuracy were not evaluated. Additional testing with human subjects is planned. The current paper addresses only the accuracy of the accelerometers as mounted in the custom seat pad and base sensors. Environmental durability and long-term performance (e.g., drift, hysteresis, non-linearity, and effects of power supply variations) are not yet established. Further validation in extended real-world conditions is needed to establish long-term accelerometer signal stability under factors such as dust, temperature and humidity swings, and variations in seat materials. Improving system ruggedness would involve waterproofing, more robust power connection and delivery options, alternative casing materials, and considerations for protection if dropped or otherwise subjected to high shock events, among other issues consistent with commercial device development. A slight underestimation of vibration at low frequencies in the seat pad sensor and a slight overestimation at the base sensor were observed, which may affect transmissibility calculations. Exposing the custom instrumentation system to a broader range of input vibration profiles is needed to establish whether the potential error in SEAT value is consistent and/or mathematically correctable. To prepare for pilot data collection in the field, additional engineering is needed to optimize the system's wake-up/sleep, operator detection, and GPS functionality. In addition, while a single FSR might suffice for detecting operator presence, the spatial arrangement of multiple FSRs appears promising as a means to coarsely classify operator posture (e.g., leaning forward or reclining) under lab conditions (Fiegel et al. 2026). Additional work is needed to validate posture classification in field data collection contexts.

Conclusions

Results demonstrate that acceleration measurements from the custom WBV instrumentation system are comparable to those from established devices in both the time and frequency domains. While subsequent data analysis currently requires external software, the system is expected to reduce operational expenses and dependence on specialized personnel to perform long-term data collection in remote locations. Although not explicitly emphasized in this paper, the overall hardware cost of the custom WBV instrumentation system is on the order of a few hundred U.S. dollars, substantially lower than comparable commercially available solutions, although the real costs of developing a novel system are in the engineering.

Although laboratory tests suggest strong agreement with reference sensors, further validation in extended real-world conditions is needed. Minor overestimations at higher frequencies and underestimation at lower frequencies, especially in the seat pad sensor measurements, emphasize the need for optimized mounting approaches and possibly refined filter designs. Continued system development could include embedding signal processing algorithms (e.g., the human vibration weighting filters) directly onto the device, thereby reducing post-processing computational overhead and enhancing usability for non-experts. Efforts to examine sensor drift over prolonged use could also bolster confidence in large-scale deployment. By addressing these areas, the system can evolve into a more robust platform, facilitating long-term monitoring and potentially guiding innovations in WBV exposure assessment practices.

Recommendations

The authors suggest integrating vibration weighting filters and summary metric calculations directly into the device to reduce the need for external software. Further testing of the force sensing resistors is recommended to determine if they can reliably detect changes in operator posture under field data collection conditions. Future studies will deploy the system in real-world conditions across different machines and seats to confirm its performance and reliability.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This research was supported by US Centers for Disease Control and Prevention (CDC)/National Institute for Occupational Safety and Health (NIOSH) through a cooperative agreement with the Great Plains Center for Agricultural Health (CDC/NIOSH grant no: U54OH007548). The material presented is solely the responsibility of the authors and does not necessarily reflect the official views of CDC/NIOSH.

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Data availability statement

Data presented in this article are not readily available because they are part of an ongoing study. Requests to access the data should be directed to Dr. Nathan Fethke.

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