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EVALUATION OF I-POD APP TO ASSESS WHOLE-BODY VIBRATION AND SEAT TRANSMISSIBILITY ON MOBILE MINING EQUIPMENT

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ABSTRACT

Researchers at the National Institute for Occupational Safety and Health (NIOSH) performed a pilot study focusing on the measurement accuracy of a mobile iOS application (app) to assess whole-body vibration (WBV) and seat performance on mobile mining equipment. The major objectives of this study were to assess the accuracy of an iPod app and determine if a pair of iPods running the iPod app were suitable to measure SEAT (Seat Effective Amplitude Transmissibility) value. The goal is to recommend a simple method to determine when a vehicle seat may need to be repaired, replaced, or adjusted. The study showed that the iPod app has the potential to serve as a low-cost tool to estimate WBV exposures to operators of mobile mining equipment. The study results were similar to those obtained by Burgess-Limerick et al. for operator WBV exposures on mining equipment. In contrast, an effort to examine seat performance using the mobile app showed greater variation between the app and the precision Siemens/LMS system selected as the "gold standard." When comparing the Siemens/LMS and iPod pair systems, SEAT values calculated using weighted-root-mean-square acceleration (a_w) resulted in a mean percent difference of 8.5$\pm$7.9%, whereas those calculated using vibration dose value (VDV) resulted in a mean percent difference of 5.5$\pm$4.4%. Additional data collection is necessary to determine what factors may be associated with this variance.

INTRODUCTION

In mining, an important need exists to prevent vibration-induced injuries through improved awareness of vibration exposures to mine workers. Off-road mining equipment operating under harsh conditions can produce whole-body vibration (WBV) and mechanical shock exposure to equipment operators. However, mining companies do not have a simple and low-cost means for assessing the WBV exposures of mobile equipment operators. Moreover, there is not an uncomplicated, affordable, yet effective way for mine managers to recognize when a vehicle seat may need to be repaired, replaced, or adjusted due to its poor vibration attenuation. This is of interest in that an off-road heavy vehicle seat can range from $400 to $3,000 or more depending on its characteristic design and features. Presently, WBV measurement systems are somewhat complex involving a recording device with other accessory instruments, such as accelerometers that must be used together with the recording device at a cost from $4,000 to $50,000 or more. Moreover, collection and analysis of this data requires complex subject area knowledge. This highlights the need to provide mining companies with a straight-forward, uncomplicated method for estimating vibration exposure.

Background

Personal electronic devices (e.g., iPhones and iPods) permeate our world today. These devices typically are equipped with various sensors that provide data and information that serve as input to the operating system. Until recently, the only methods to measure WBV required costly measurement systems and technical expertise to analyze the data. Researchers at the University of Queensland (UQ) have developed the iPod app to provide a simple and low-cost way to estimate WBV exposure [1, 2]. The application collects accelerometer data and calculates frequency weighted estimates of WBV exposure according to the methods described in ISO2631-1:1997 [3]. The iPod app has been tested for use on a 5th generation iPod Touch running iOS7 operating system. The results of field studies examining the iPod app have been favorable [4, 5].

The National Institute for Occupational Safety and Health (NIOSH) has performed a recent study focusing on the measurement accuracy of the iPod app. The major objectives of this study were to assess the accuracy of the iPod app and determine if a pair of iPods running iPod app were suitable to measure SEAT value. Consequently, the purpose of this research was to determine whether the application could be an affordable and effective tool for monitoring WBV exposure and seat performance on mobile mining and quarry equipment.

EFFECTS OF VIBRATION EXPOSURE

Whole-body vibration places a significant burden on the health and safety of exposed mine workers. Off-road mining equipment operates on rough surfaces under harsh operating conditions that produce WBV and mechanical shock. WBV exposure can cause muscles to contract in a voluntary or involuntary way and lead to fatigue or a lowering of motor performance capacity [6]. Research points to WBV as a contributing factor in the development of musculoskeletal disorders (MSDs) of the spine among workers exposed to a vibration environment [7, 8, 9, 10, 11, 12, 13, and 14]. Low-back pain (LBP) is a prominent and unfavorable health effect of WBV. NIOSH has reported a significant positive association between WBV exposure and LBP in 15 of 19 WBV research studies reviewed; its highest ranking descriptor of 'strong evidence' was assigned to the WBV-LBP relationship [15]. Additionally, NIOSH mine-site field investigations have reported evidence of WBV exposure levels for mine haul trucks and front-end wheel loaders that fall within or above the Health Guidance Caution Zone (HGCZ) of existing international and national recommended standards [16]. Weighted root-mean-square accelerations – a_w – (measured along the three orthogonal axes and normalized to an 8-hour shift have ranged from 0.19 m/s² to as high as 5.64 m/s² for a more recent study [17]. This latter, larger number portrays an order of magnitude more than 6 times the exposure limit of the ISO/ANSI standard.

MEASURES OF INTEREST EXPLAINED[1]

Weighted-root-mean-square acceleration (a_w) is frequency-weighted acceleration, expressed in m/s^2, and used to describe levels of vibration exposure in three directions: X (fore-aft), Y (side-to-side), and Z (vertical). See a visual description in Figure 1. The Z-axis is typically of greatest interest and can be associated with the greater risk for back injury/pain. The term a_w (8) represents levels normalized to an 8-hr shift. Equations 1 and 2 shows how a_w is calculated and determined for an 8-hour shift, respectively.

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

$a_w(t)$ is the weighted acceleration as a function of time,

T is the period.

$$A_z(8) = a_{wz}\sqrt{\frac{T_{exp}}{T_0}}$$

a_{wz} is z-axis weighted acceleration,

T_{exp} is duration of measured vibration exposure,

T_0 is the reference duration of 8 hours.

Crest Factor is the ratio of the maximum instantaneous peak value of the frequency-weighted acceleration signal to its root mean square value (Equation 3). The crest factor may be used to investigate if the basic evaluation method is suitable for describing the severity of the vibration in relation to its effects on humans. The basic evaluation method is normally sufficient for vibration with crest factors below or equal to 9. A crest factor greater than 9 indicates the data should be examined for jars and jolts.

$$C = \frac{|a_{w,peak}|}{a_{w,rms}} \tag{3}$$

a_{wz} is the z-axis instantaneous peak weighted acceleration,

$a_{wz_{RMS}}$ is the z-axis weighted-root-mean-square acceleration

Vibration Dose Value (VDV) is a cumulative measure of vibration received by a person during the measurement period. Equation 4 shows how VDV is calculated. This measure is more sensitive to peak levels and transients and is expressed in m/s$^{1.75}$. The term VDV (8) represents levels normalized to an 8-hr shift (Equation 5).

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

$a_w(t)$ is the instantaneous frequency weighted acceleration,

T is the duration of measurement.

$$VDV_z(8) = VDV_z\sqrt{\frac{T_{exp}}{T_0}} \tag{5}$$

VDV_z is z-axis vibration daily value,

T_{exp} is duration of measured vibration exposure,

T_0 is the reference duration of 8 hours.

Seat Effective Amplitude Transmissibility (SEAT) value is the ratio of output vibration measured on the driver/operator seat pad surface divided by the input vibration measured on the cab floor. It is an assessment of the seat isolation efficiency for vibration transmitted through the seat from the chassis. SEAT values above 1.0 indicate the seat is amplifying vibration to the driver/operator; whereas, SEAT values below 1.0 indicate the seat is attenuating the vibration. Seat values were computed by the a_w and VDV methods as shown in Equations 6 and 7.

[1] Reference numbers [3, 18, 19, and 20].

$$SEAT\% = \frac{a_{w,seat}}{a_{w,floor}} \times 100 \quad (6)$$

$$SEAT\% = \frac{VDV_{seat}}{VDV_{floor}} \times 100 \quad (7)$$

Health Guidance Caution Zone (HGCZ) is a metric that uses vibration level and duration to evaluate when a subject is at risk of overexposure to WBV. The boundaries expressed in frequency-weighted acceleration and VDV are shown below for both the ISO/ANSI and European Union Good Practices Guide (EUGPG) for Directive 2002/44/EC. These boundaries represent the minimum health and safety requirements for exposure of workers to the risks arising from WBV. Levels below the zone (or Exposure Action Value, or EAV) indicate health effects that have not been clearly documented. Those levels within the zone indicate caution with respect to potential health risks, and levels above the zone (Exposure Limit Value, or ELV) indicate that health risks are likely. Tables 1 and 2 display the EAVs and ELVs in terms of a_w and VDV.

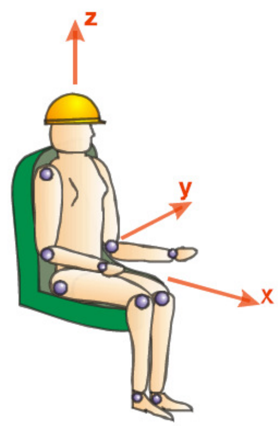

Figure 1. A pictorial description of the three axes (Griffin et al., 2006).

Table 1: Health Guidance Caution Zone Limits in Frequency-Weighted Acceleration (a_w).

Standard/EU Directive	*Lower Boundary—EAV*	*Upper Boundary—ELV*
ISO/ANSI	0.45 m/s^2	0.90 m/s^2
EUGPG	0.50 m/s^2	1.15 m/s^2

Table 2: Health Guidance Caution Zone Limits in Vibration Dose Value (VDV)

Standard/EU Directive	*Lower Boundary—EAV*	*Upper Boundary—ELV*
ISO/ANSI	8.2 m/s$^{1.75}$	16 m/s$^{1.75}$
EUGPG	9.1 m/s$^{1.75}$	21 m/s$^{1.75}$

METHODS

NIOSH researchers measured WBV for operators of mobile mining equipment as they performed their normal work. A Siemens SCADAS–SCR05 16-channel data recorder with 24-bit resolution (Siemens PLM Software, Troy, MI) was used as the reference system and compared to the iPod Touch devices (iPod A1509, iOS 9.3.5, 2013, Apple Inc., Cupertino, California) running the WBV app. The SCADAS recorder was connected to two triaxial accelerometers, PCB 356B40 seat pad and PCB 356B18 (PCB Piezotronics, Inc., Depew, NY) and collected data were stored in flash memory on a SD card. The WBV app uses the built-in triaxial accelerometer in the iPod to collect and process acceleration data and calculate frequency-weighted RMS acceleration (a_w) and vibration dose value (VDV). The results presented in this paper focus on vibration in the Z direction, as it is associated with greater risk for back injury/pain.

One iPod Touch device was placed under the front-most portion of the circular seat pad accelerometer according to the WBV app User Manual and a second iPod was placed on the cab floor near the PCB 356B18 accelerometer. Figures 2 and 3 show the instrumentation setup.

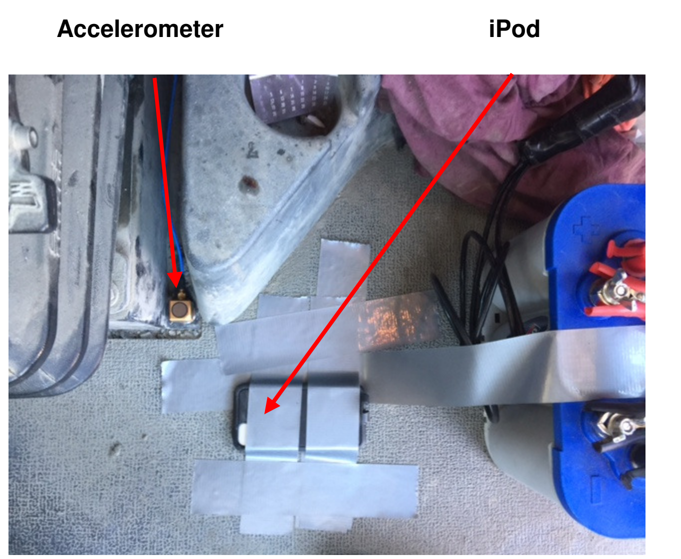

Figure 2. Placement of accelerometer (PCB model 356B18) and iPod Touch on the floor of the vehicle cab for measuring chassis transmitted vibration.

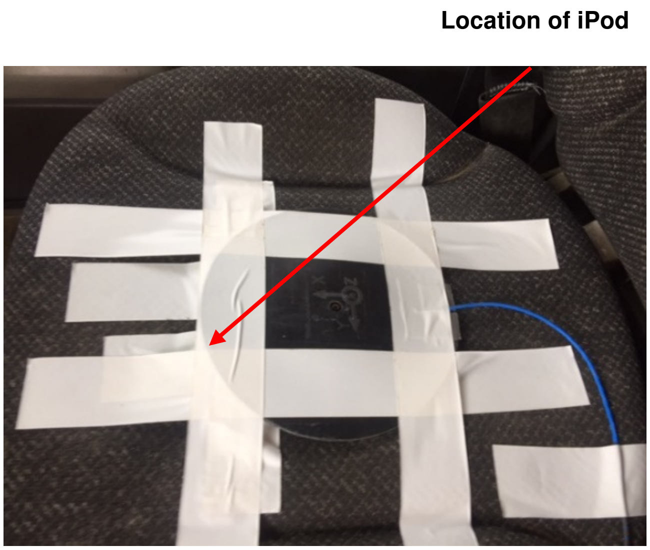

Figure 3. iPod Touch for measuring seat transmitted vibration using PCB model 356B40 seat pad; iPod Touch is positioned under the front portion of the seat pad for measuring vibration at the driver/seat interface.

MATLAB was utilized to analyze the data collected in this study. The tri-axial acceleration data, collected with the SCADAS system, were trimmed exclusively to obtain a period of active operation. The acceleration data were frequency-weighted according to the ISO/ANSI standards and then analyzed to determine a_w and VDV values. Computed values of a_w and VDV included instantaneous and cumulative measures and those normalized to an 8-hour shift. In turn, the results were compared to the criteria presented in the ISO/ANSI and EU Directive 2002/44/EC standards. SEAT values (output/input) were then obtained using two calculation methods a_w and VDV; where, VDV is recommended for high crest factors, e.g., those greater than 9.

Tri-axial acceleration data were also recorded simultaneously with the iPod pair. As the two devices were not synchronized with a central clock, the analysis procedure differed slightly from the SCADAS measurements. Due to differing measurement start times, the acceleration time series were manually aligned, anchored by the visibility of equipment ignition in the waveform. Once aligned, the data was analyzed in the same manner as the SCADAS data utilizing the same MATLAB script, resulting in the same frequency-weighted a_w and VDV metrics. Moreover, data were acquired at 512 Hz for the Siemens/LMS system and ~ 90 Hz for iPod system.

FIELD STUDY

A field study was conducted using the app to collect data for 13 mobile mining machines in operation at one sandstone mine and three limestone mine sites located in central and southwestern Pennsylvania and northern Virginia. Table 3 provides a description of the mine locations, commodities, and equipment.

Table 3. Description of the mine locations, commodities, and equipment.

Commodity	*Location*	*Type of Operation*	*No. of Haul Trucks*	*No. of Front-End Wheel Loaders*
Limestone	Western PA	Surface	2	2
Sandstone	Northern VA	Surface	1	2
Limestone	Central PA	Underground/ Surface	2	1
Limestone	Southwestern PA	Surface	1	2

RESULTS

The results obtained demonstrated very good agreement between the two systems for operator WBV exposure normalized to an 8-hour shift (Figures 4 and 5). Again, the results presented herein apply to vibration in the Z direction, since it is associated with greater risk for back injury/pain.

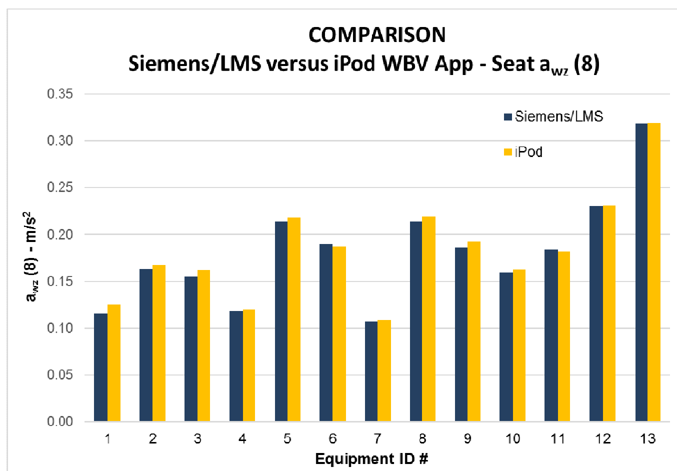

Figure 4. a_{wz} measured at the seat and normalized to an 8-hr shift for equipment ID #s shown above.

Absolute differences in percent for a_w when comparing the Siemens/LMS and iPod measurement systems ranged from 0.1% to 8.5%. Twelve of the 13 instances showed percent differences for a_w of 4.2% or less. Absolute differences in percent for VDV measures comparing the Siemens/LMS and iPod measurement systems ranged from 0.3% to 18.8% percent. Eleven of the 13 instances showed percent differences of 4.4% or less. Moreover, a_w and VDV levels showed strong Pearson correlation coefficients of 0.998 and 0.981, respectively.

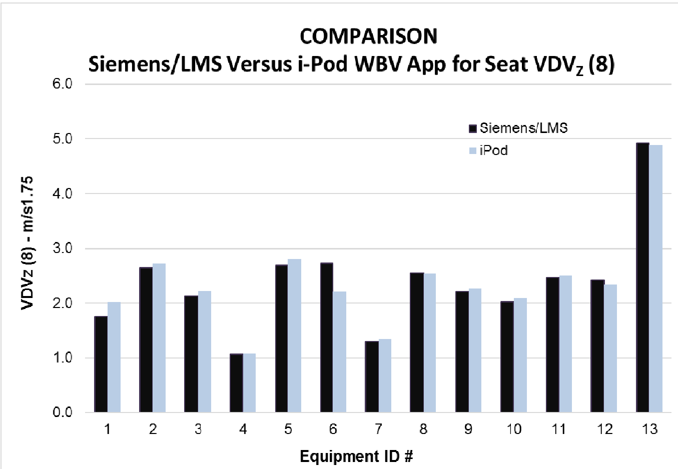

Figure 5. VDV_z measured at the seat and normalized to an 8-hr shift for equipment ID #s shown above.

Figures 6 and 7 shows z-axis SEAT values calculated as the ratio of seat output levels of a_w and VDV, obtained by the seat-mounted iPod and seat pad accelerometer, divided by the seat input levels of a_w and VDV obtained from the accelerometer and iPod fastened to the cab floor. SEAT values appearing above the horizontal line at 1.0 represent amplification of vibration, whereas values appearing below 1.0 represent attenuation of vibration. When comparing the Siemens/LMS and iPod pair systems, SEAT values calculated using a_w (and excluding four potential outliers ID #'s 3, 6, 9, and 12) resulted in absolute percent differences ranging from 0.8 % to 21% with a mean absolute percent difference of $8.5\pm7.9\%$. Those calculated using VDV (and excluding four ID #'s 1, 2, 5, and 10 showing percentages greater than 15%) resulted in absolute percent differences ranging from 0.7 % to 8.1 % with a mean absolute percent difference of $4.4\pm2.8\%$. The VDV method is recommended for high crest factors (greater than 9) [19].

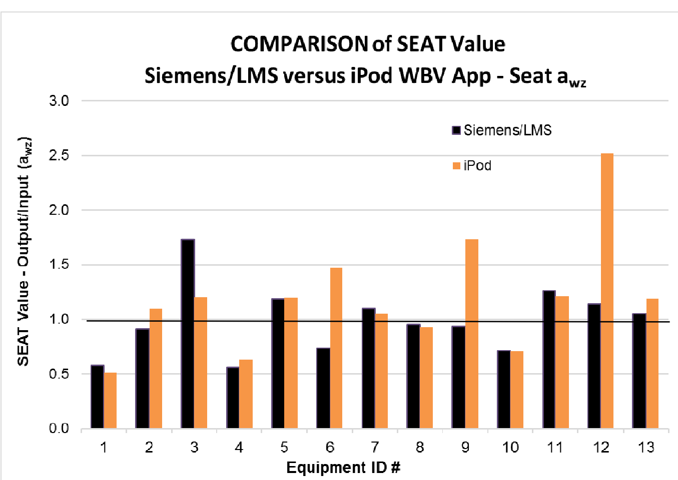

Figure 6. SEAT values computed using the frequency-weighted acceleration, a_w, method.

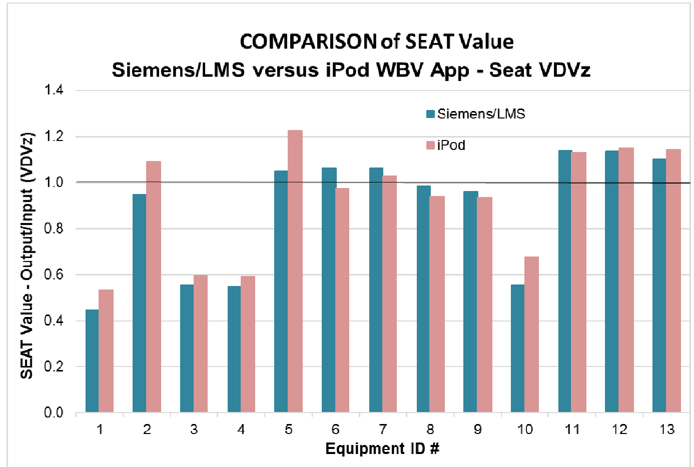

FIGURE 7. SEAT Values computed using the VDV method.

DISCUSSION

This study showed that the iPod Touch using the WBV app has the potential to serve as a low-cost tool to estimate operator WBV exposures on mobile mining equipment. This NIOSH study indicated results similar to those obtained by Burgess-Limerick et al. for operator exposures. Burgess-Limerick et al. have performed studies with the iPod app in surface mining operations to assess WBV exposure levels [1, 2, and 4]. In their report, Burgess-Limerick and Lynas [5] obtained 96 vertical measurements of acceleration using the iPod app and a commercially available vibration measurement device, the Svantek SV 106. The results showed average variance between the SV 106 and the iPod app was 0.033 m/s^2. Moreover, the average constant error for the iPod measurements was 0.013 m/s^2 with a standard deviation of constant error at 0.039 m/s^2. They concluded that using the application installed on an iPod Touch provided a 95% confidence of $\pm$ 0.07 m/s^2 for the vertical direction. Killen [21] also investigated the iPod app and compared it to a commercially available system that served as a "gold standard." In laboratory and field evaluations, the iPod app demonstrated excellent agreement with the gold standard device (series 2, 10G tri-axial accelerometer – NexGen, Ergonomics, Montreal, QC, Canada and P3X8-2C DataLogII data-logger – Biometrics, Gwent, United Kingdom).

To date, there have not been any studies using the application to assess seat performance and it appears the NIOSH study may be the first attempt to do so. Results for SEAT value in the NIOSH study exhibited greater variability between the two systems. When reviewing Z-directional crest factors, the Siemens/LMS system showed values higher than 9; whereas, the iPod crest factors were only significantly below 9 in two cases. The acquisition frequency of the iPods is quite low for this purpose and aliasing may have contributed some uncertainty. One possible cause of measurement error between the two systems may be the impulsive overloading of the lower quality sensors in the iPods. Additional data collection is necessary to understand the factors associated with the variance for the SEAT values computed. Future laboratory testing of i-Pod and Siemens/LMS systems, using controlled frequency and acceleration inputs, is a future consideration for scrutinizing possible factors.

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