

Exposure monitoring system for day-long vibration and palm force measurements

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Abstract

A small, highly portable data-logging system, including a palm-mounted adapter containing an accelerometer and a force sensor, was developed to record user-specific tool-operating times, hand-transmitted vibration, and palm forces throughout all, or a representative part, of an 8-h workday. The microprocessor-based device has proved to be cost-effective, robust, and flexible and can be applied across a wide range of occupations and occupational settings involving exposures to vibration.

Relevance to industry

When considering past research, there still remains a clear need for a methodology that accurately measures day-long vibration exposures over the course of the entire working day regardless of work cycle times and work patterns. The Vibration Exposure Monitor (VEM) system enables hand–arm vibrations to be more accurately characterized and so can assist in modeling exposure–response relationships in vibration-intensive work environments.

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1. Introduction

Over the past two decades, there have been significant reductions in industrial exposures to hand–arm vibration, especially when specific tools and work processes have been redesigned to incorporate anti-vibration and ergonomic principles. Nevertheless, Hand–Arm Vibration Syndrome (HAVS) remains a significant occupational health problem as disease symptoms continue to occur even when vibration exposure levels believed to incur low risks have been reached. Burström et al. (2004) studied metal workers where tools produced low vibratory exposures with frequency-weighted accelerations between 2.1 and 2.5 m/s² but the prevalence of vascular (39%) and neurological symptoms (47%) still existed, with the vascular incidence rate being 24.2 cases per 1000 exposure years. In a study of automobile mechanics, Barregård (2003) and Barregård

et al. (2003) determined through intermittent observations on a representative sample population that the average duration of daily power tool use was 14 min with 80% of the tool use involving nut runners having an average weighted acceleration of 3.6 m/s². They detected Raynaud's Phenomenon in 24% of the workforce (10% prevalence over 10 years), with an incidence rate of 20 cases per 1000 exposure years. Based on the European Directive (ED) 2002/44/EC, a 14-min daily exposure of 3.6 m/s² should have provided an adequate margin of safety. In a recently reported study of vibration-exposed Korean shipyard workers, Jang et al. (2002) found vascular symptoms in 22.7% of the exposed workers and neurological symptoms in 78.2%. The prevalence is almost identical to that cited among American (Letz et al., 1993) and Italian (Bovenzi et al., 1980) shipyard workers studied in the 1980s using less advanced tools and work processes that did not incorporate modern anti-vibration and ergonomic principles.

The accepted approach to measuring hand–arm vibration follows the methods and procedures specified in ISO

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5349 (Parts 1 and 2) (2006). One aspect of ISO 5349 is the standardized estimation of exposure by means of energy averaging throughout the duration of a workday (specified as 8 h). Since day-long monitoring of exposure is infrequently performed, a representative day-long exposure constructed from measurements conducted during part of the workday is employed. Often, ‘simulated’ work tasks with extremely short cycle times are performed in order to determine the magnitudes of the hand-transmitted vibrations. Eight-hour exposures are then calculated using estimates of individual tool-use time over the course of the workday as reported by the worker or from a time-sampled observation made by the investigator. This approach has the potential to produce significant deviations from actual exposure durations. For example, Fig. 1 shows the average exposure duration for six different work processes in a truck manufacturing facility as measured using a self-reported questionnaire and by physical observation (Cherniack et al., 2006). These results suggest that traditional methods can seriously misjudge the duration of exposure causing a lack of correspondence between estimated and actual exposure summations. As a result, instrumented measurements appear necessary to authenticate exposure magnitudes and durations. Under ideal conditions, day-long vibration exposures should be measured over the course of the entire working day regardless of work cycle times and work patterns.

Data-logging systems remained impractical due to computational processor and storage media size, speed, and cost until the late 1990s, when the development of novel storage and processing technologies began to emerge.

Anderson and Lyons (2001) offered a critical review of data-logging technology and predicted that digital-based equipment would provide the best solution for human-based data logging. Data-logged durations, signal resolution, and measurement parameters will greatly increase as digital storage media technology advances. Regardless of the technological limitations governing data-logging advancement, it has been implemented for use in a wide range of biomechanical risks within the occupational setting. Estill et al. (2000) used data loggers, termed activity monitors (Model 7164, Computer Science and Applications Inc., Shalimar, FL), sampling at 10 Hz from a wrist-mounted accelerometer to characterize upper limb motion in two separate industrial populations. Byström et al. (2002) used data loggers (Logger Teknologi HB, Åkarp, Sweden) sampling from inclinometers and surface electromyographic electrodes to evaluate the physical workload on the neck and upper limb during computer-aided design work. In vibration-related research, Radwin et al. (1990) measured exposure durations using a tool-mounted, battery-powered data logger sampling at 1–2 samples per second from a tool-mounted uni-axial accelerometer. Three metal finishing tasks involving sander-type tools were monitored over the course of approximately 60 min to yield predicted daily exposure times ranging from 42 to 63 min using the frequency-weighted energy equivalent acceleration equation of ISO 5349 (2006). Neitzel and Yost (2002) also estimated the hand–arm vibration exposures experienced by forestry workers performing tasks involving chainsaw operations using a hand-held sound level meter (2231 Type 1, Bruel & Kjaer, Denmark) equipped to

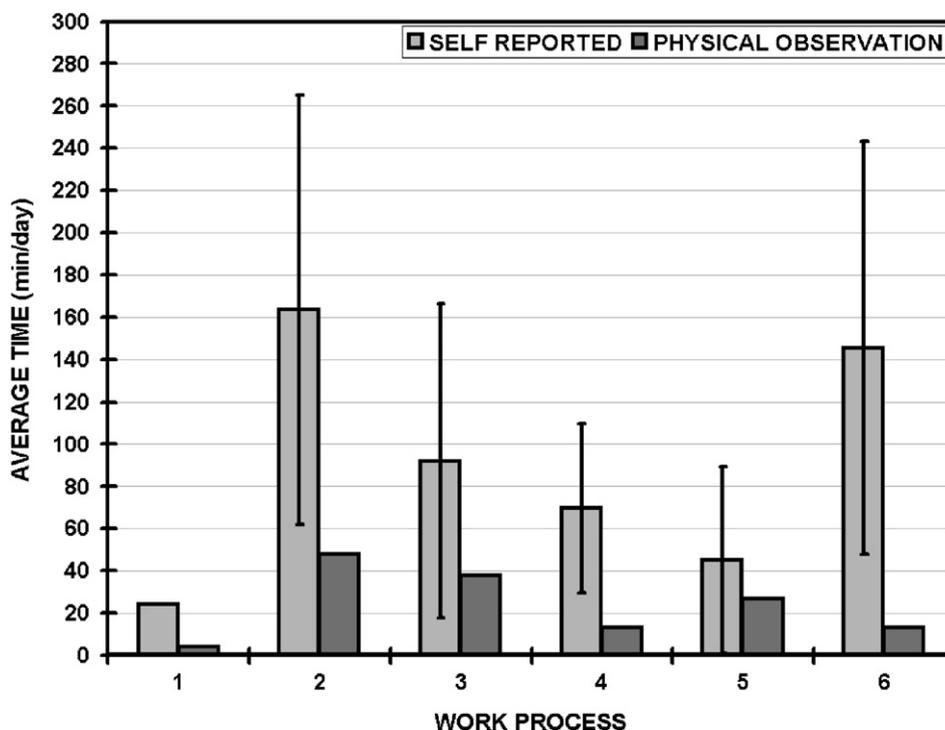


Fig. 1. Variation in exposure duration by process from self-reported questionnaires and from physical observations.

measure vibration. The averaged axis-specific and summary frequency-weighted acceleration component values were recorded over very short durations (~2 min) involving one or more cycles of the task or tool and, in conjunction with subjective survey results detailing tasks and tools, day-long exposure levels were projected.

Small personal vibration dosimeters are now commercially available from manufacturers, such as Brüel & Kjær (Nærum, Denmark), Larson-Davis (Provo, UT), Svantek (Warszawa, Poland), and Quest Technologies (Oconomowoc, WI), that calculate, record, and display vector sums and energy equivalents. Since these devices require the accelerometers to be mounted directly on the tool, they are incompatible with work patterns that involve changing or putting down tools. In addition, these commercial systems do not allow for the characterization of the transmission of vibration from the tool handle to the hand by monitoring the grip forces. O'Boyle and Griffin (2004) showed that variations in applied force can alter material transmission characteristics by 50% or more. Lombard and Holt (1982) reported that tool handle vibration measurements can vary as much as 200% in some octave bands when performed by different laboratories. This effect is most likely due to the variation in hand–tool coupling, which will directly influence vibration levels recorded at the tool handle (Brammer, 1977; Färkkilä et al., 1979). This suggests that the measurement of applied grip force is essential for determining the exposure of the hand to vibration.

In an attempt to identify an appropriate palm mount to characterize the absorption of vibrational energy by the hand during tool use, Burström and Lundström (1998) developed and tested four adapters employing different acceleration and force sensing technologies. Although a design was suggested, no attempt was made to implement it in field-based measurements. Gillmeister and Schenk (2001) developed a large palm-mounted adapter, which employed a tri-axial accelerometer, a force transducer, and a contact sensor, to measure hand-transmitted vibration and grip force. The adapter was used in conjunction with a large, backpack-sized data logger (Gillmeister et al., 2001) to record and calculate the frequency-weighted accelerations over long work periods. The bulky size of the adapter limits its practical use to large-handled tools that do not require constant adjustments in grip orientation and fine hand movements, such as those needed during small tool use. The ability of the adapter to characterize exposures

involving frequencies up to 1.25 kHz as recommended in ISO 5349 (ISO, 2006a, b) is unclear. Frequencies up to 1.5 kHz have been reported by Burström (1990) and Jandák (1990) to be important when considering the absorption of vibrational energy by the hand. Furthermore, the size of the backpack data logger will not allow workers the freedom to work in confined or narrow spaces without hindrance.

2. Apparatus and methods

2.1. Palm-mounted adapter

Two sensors, a uni-axial accelerometer (Model 352C22, PCB Piezotronics, Depew, NY), of 6.35 mm diameter and 3.56 mm thickness, and a force sensitive resistor (FSR) (Model 400, Interlink Electronics, Camarillo, CA), of 5.00 mm diameter and 0.30 mm thickness, were mounted on the palm using a custom designed housing constructed entirely out of aluminum. The housing was sheathed in a semi-rigid plastic and was secured to the palm using elastic straps (Fig. 2). The palm mounting system, or palm adapter, was not secured tightly, but was allowed to shift and roll slightly by design in order to provide a small margin of movement during its use to reduce the potential for sensor, sensor cable, or strap breakage and to allow for hand flexibility and safe tool operation. The force sensor and accelerometer were placed atop one another within the sheathing and aluminum housing, and oriented so that their primary activation axes were aligned. The adapter was situated on the palmar surface so that the overall activation axis (i.e., both sensor activation axes taken as one) was perpendicular to the palmar surface when 'sandwiched' between the tool handle and the hand. There was no reference to the axes defined in ISO 5349 (ISO, 2006a, b) because the palm adapter was not rigidly attached to the palm.

The palm adapter was secured to the palmar aspect of the dominant hand between the distal and proximal transverse palmar creases using only a thin nylon elastic strap and was designed to form a continuous surface about the entire palm by resting in the pocket formed by the palm when the hand is in a grasping posture. It was small enough in size to allow the subject to wear several layers of gloving with very little to no interference. The wires of the palm adapter were held in place along the posterior arm,

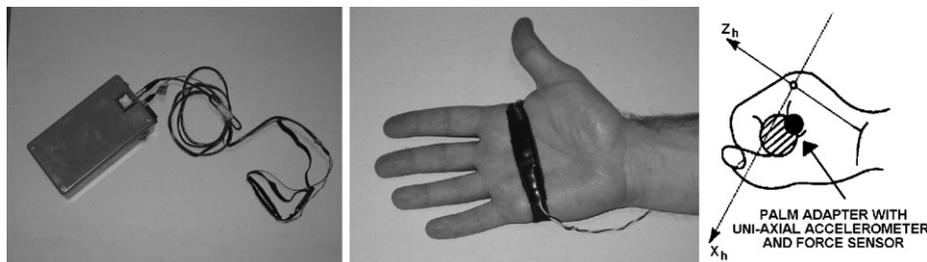


Fig. 2. Vibration Exposure Monitor (VEM) system including the palm-mounted adapter and adapter placement.

shoulder, and back, using surgical tape that maintained its hold under dirty and/or sweaty conditions.

Adequate representation of acceleration and palm force patterns were validated through laboratory studies involving an electro-dynamic shaker outfitted with a handle that was instrumented with an accelerometer and strain gage load cell. The frequency responses of 11 palm adapters were measured using a dynamic signal analyzer (SR785, Stanford Research Systems, Sunnyvale, CA) for combinations of two stimulus conditions (i.e., chirp and white noise) and four grip force conditions (i.e., 25, 50, 75, and 100 N). Fig. 3 shows the average frequency response of 11 palm adapters measured at 100 N of grip force with a chirp stimulus and was observed to be essentially flat up to approximately 3 kHz. The deviation in response between adapters was, typically, ± 1 dB up to 2 kHz. This was observed to be a typical result for each of the conditions, even when considering the adapter's ability to shift and roll allowing the activation axis to become non-perpendicular with the palmar surface and tool handle. During other pilot studies involving actual tool use, the measurement direction was not observed to vary substantially, even with tools requiring frequent adjustments in grasping strength and hand positioning.

2.2. Vibration Exposure Monitor (VEM) system

The VEM system was driven by a low-power Motorola 68332 microprocessor with a PIC 16C64 coprocessor, which functions as a tunable system clock with frequencies from 160 kHz to 16 MHz, and contains 256 kb of flash

EEPROM memory for program storage and 1 Mb of resident RAM memory for data storage. This unit is manufactured specifically as a battery-powered data logger (Tattletale Model 8v2, Onset Computer, Onset, MA) and draws less than 250 μ A in low-power mode and 150 mA under the most strenuous conditions. It has the capability of hosting and executing complex protocols to control, collect, and process the sampled data from up to 8 analog channels using 12-bit sampling at a single-channel maximum frequency of 100 kHz. It weighs approximately one ounce, is resistant to shock and vibration, and can operate over a -40 to 65 °C temperature range.

Custom analog circuitry was interfaced with the Tattletale computer, as shown in Fig. 4, to pre-process the signals originating from the acceleration and force transducers mounted on the subject's palm. Anti-aliasing and noise rejection, at 4 and 1250 Hz cutoffs, were accomplished for all signals using operational amplifiers (OP270, Analog Devices, Norwood, MA) with a low offset voltage (75 μ V maximum), low offset voltage drift (1 μ V/°C), and low noise (5 nV/ \sqrt Hz at 1 kHz maximum). A dedicated operational amplifier (OP297, Analog Devices, Norwood, MA), with a lower offset voltage (50 μ V maximum), slightly higher offset voltage drift (6 μ V/°C), and higher noise (17 nV/ \sqrt Hz at 1 kHz maximum), was used, because of its low operating current, to frequency weight the acceleration signal by means of a bandpass filter that was designed using the filter specifications provided in ISO 5349 (ISO, 2006a, b). Another dedicated operational amplifier (i.e., OP297) was used as an inverting amplifier to drive the force transducer. Once the accelerometer signal was

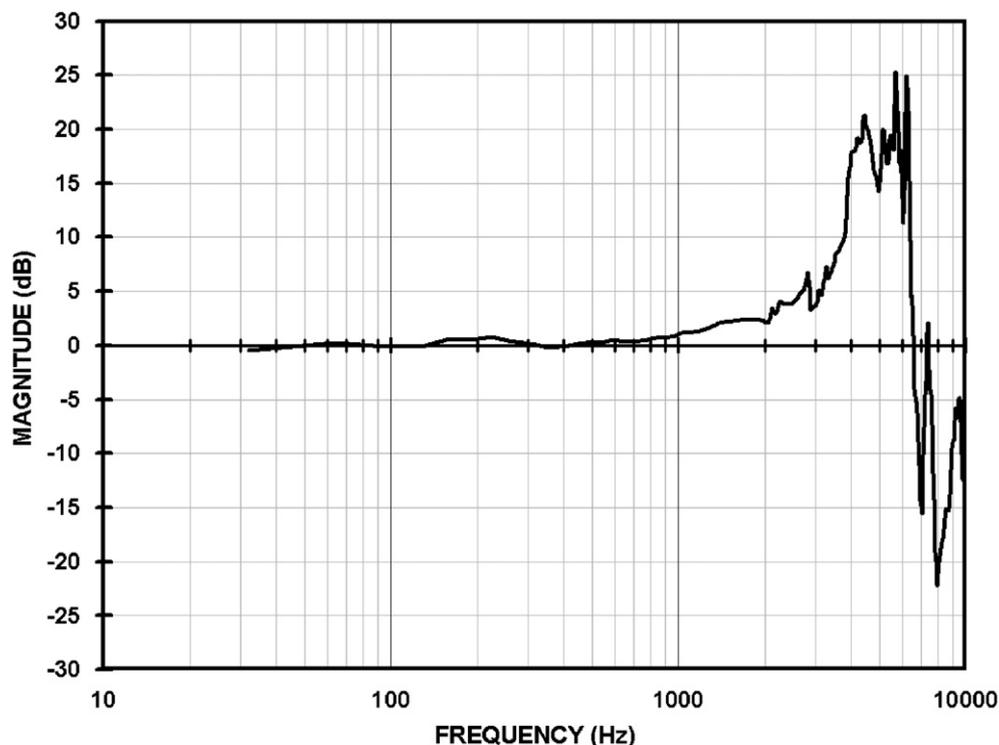


Fig. 3. Average frequency response of 11 palm adapters at 100 N of palm force.

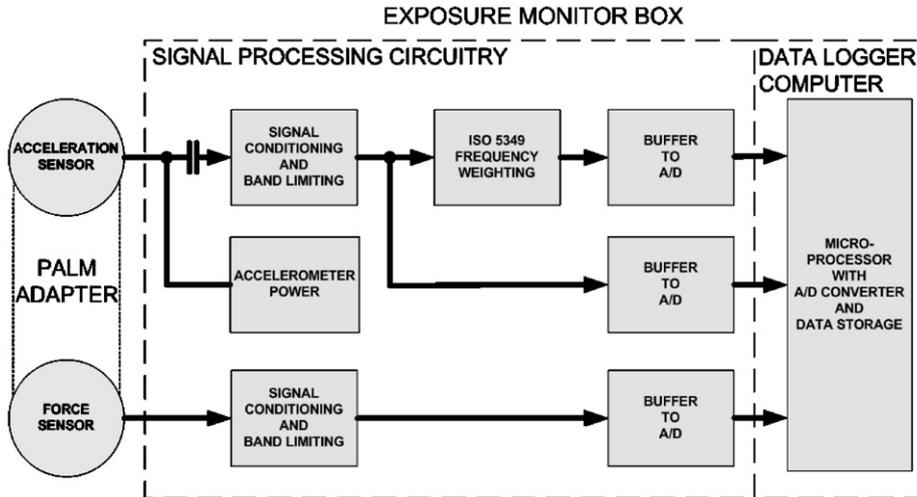


Fig. 4. VEM system block diagram.

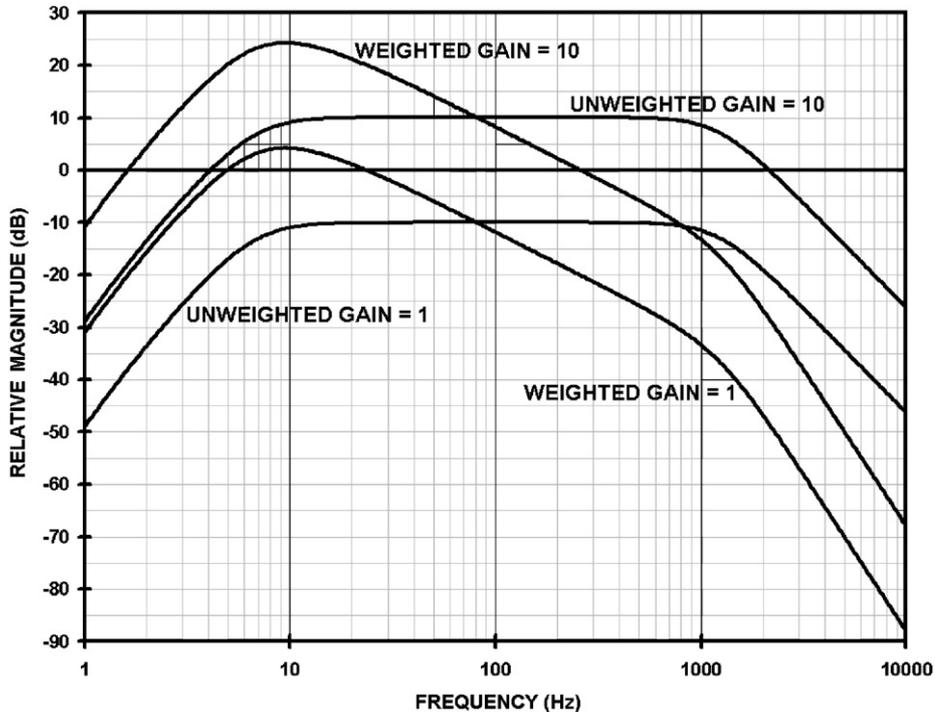


Fig. 5. Frequency response of the acceleration channels for both gain settings.

conditioned, it was divided into two channels to provide for raw and frequency-weighted vibration measures. The circuitry for each transducer had a selectable gain setting to establish sensor sensitivity and to accommodate different ranges of accelerometers and FSRs, and each signal was electronically buffered prior to the A/D converter. The low impedance output of the custom circuit permitted anti-static discharge protection to be provided to the input of the A/D converters.

Each of the three data channels (i.e., un-weighted acceleration, weighted acceleration, and palm force) was observed to have a characteristic level of electronic noise, which was most likely due to the inherent noise levels

associated with the operation of the Tattletale microprocessor and A/D converter. The average root mean square (RMS) noise levels of the analog signals at the output of the anti-aliasing filters and prior to the analog-to-digital converter were measured to be 2.5 mV for the un-weighted and 2.0 mV for the weighted channels and 1.3 mV for the palm force channel. The frequency response of the acceleration channels for both gain settings were measured using a dynamic signal analyzer (i.e., SR785) with a swept sine wave stimulus and is presented in Fig. 5.

Three 9 V batteries, with a rated capacity of 570 mAh, were used to power the entire system. Two batteries were used to power the Tattletale computer, which required a

supply between 7 and 15 V, and to provide a clean +5 V to the analog circuitry, while the remaining battery was used to provide a clean –5 V. All supply voltages were regulated using micro-power linear voltage regulators (LT1129 and LT1175, Linear Technology, Milpitas, CA), with operating currents of 50 μ A (LT1129) and 45 μ A (LT1175) and a maximum output current of up to 800 mA. The output current, drawn between ± 5 V by the operational amplifiers, did not overload the linear regulators. In addition to amplification and filtering, the ICP-type accelerometer was connected to an isolated single-output DC-to-DC converter (LME0515S, C&D Technologies, Raleigh, NC), with output ratings of up to 15 V and 16 mA, to provide a constant current source regardless of battery voltage. This circuit was powered from the –5 V power line to optimize the utilization of battery resources. The FSR, which acts as a variable resistor once activated, was supplied with –5 V and an inverting operational amplifier circuit was used to detect changes in the output voltage as force was applied.

The VEM system was programmed with two modes of operation: run mode, which was an active mode requiring the data logger to sample and calculate data, and sleep mode, which was an inactive, low-power mode, requiring the data logger to maintain power for data retention and offloading. Since the memory storage of the VEM system was RAM-based, data retention was protected by triggering the sleep mode once the battery powering the Tattletale was observed to reach a critical voltage (i.e., <7.5 V). In run mode, the system was observed to operate reliably for up to 12 h and data was retained for up to 72 h once the sleep mode was activated.

The VEM system box was $80 \times 50 \times 150$ mm³ in size and weighed approximately 500 g, including batteries (Fig. 2). It functioned by using two switches: one switch to engage battery power to the signal processing circuitry and the microprocessor (i.e., on/off switch), and the second switch to change the state of the system from sleep mode to run mode where data is sampled, processed, and stored. The on/off switch contained an LED to indicate the status of the system using a series of blinks: (1) ready, which was indicated by steady illumination; (2) data sampling and processing; (3) sensor or system interruption, or error; or (4) system state change (i.e., run/sleep modes). Both switches were protected by a clear plastic cover to prohibit accidental activation during use of the exposure monitor.

2.3. System calibration

A connector was implemented in the design to allow access to all the analog signals at the output of the anti-aliasing filters and prior to the analog-to-digital converter. A hand-held, battery-powered oscilloscope was connected prior to the measurements to check for signal integrity and sensor function. The weighted and un-weighted acceleration output of the accelerometer was verified using the oscilloscope and a hand-held calibration vibration exciter (Type 4294, Brüel & Kjær, Nærum, Denmark).

Once the palm adapter was mounted on the subject, the calibration of the FSR was accomplished using another connector that accepted a push-button switch. From the sleep mode state, the connection of the switch automatically put the VEM system into the FSR calibration mode. Each subject was required to perform a series of grips following a randomized sequence of normalized palm force magnitudes ranging from 0 to 20 lb in 2.5 lb increments using a modified, commercially available, grip dynamometer (Grip-D, TKK 5401, Takei, Tokyo, Japan). The output voltage of the FSR that corresponded to each palm level was recorded by the VEM system by depressing the switch and was later retrieved, as part of the data file, once data collection was complete. A non-linear curve fitting algorithm using the power law formula (i.e., $y = ax^b$) was applied to the calibration data to generate a calibration curve to convert logged voltages to force.

The calibration procedures constantly verified the sensitivity and performance of both sensors. A palm adapter was not used if either sensor was compromised as a result of damage or deterioration and was subsequently repaired.

2.4. Data collection and processing

A C-based protocol was developed to optimally govern the overall operation of the VEM system including data sampling, calculation, and storage, from the three analog channels. Data were sampled and stored over a 15-s interval at a frequency of 3 kHz per channel during which the microprocessor was instructed to maintain a low clock speed in order to minimize power consumption. This was followed by a 45-s interval required for calculation of the vibration exposure and the average exerted palm force. The observed maximum and minimum values for all sampled data were also computed. The calculated results were then archived in binary format after which the data sample was discarded. The 1-min data collection and processing cycle was repeated until the VEM system was put into sleep mode either by user selection or a critically low-voltage condition. Once the exposure monitoring was completed, the data were retrieved from the VEM system via a serial port connection and converted into ASCII text format for analysis using a MatLAB (Mathworks, Natick, MA) conversion routine.

The vibration magnitudes measured by the VEM system were characterized in terms of the second and higher even-order mean values (i.e., RMS, the *root mean quad* (RMQ), and the *root mean oct* (RMO)) for both frequency-weighted and un-weighted acceleration data sets. The generalized expression for the calculation of the acceleration magnitudes, a_{RM} , is given by

$$a_{RM} = \left[\frac{1}{T} \int_0^T [a(t)]^m dt \right]^{1/r}, \quad (1)$$

where the integration is performed for a time T , which is set to a value of 15 s in accordance with the 15-s sampling interval, and m and r are constants describing the moment and root of the acceleration function, $a(t)$, respectively (Brammer and Peterson, 2003). For the RMS, which is the most common metric used to express the magnitude of

hand-transmitted vibration, $m = r = 2$ and, for the higher-order values, the RMQ and RMO, $m = r = 4$ and $m = r = 8$, respectively.

The higher, even-order mean values correspond more closely to the peak values of the acceleration waveforms and may be more appropriate for assessing impulsive

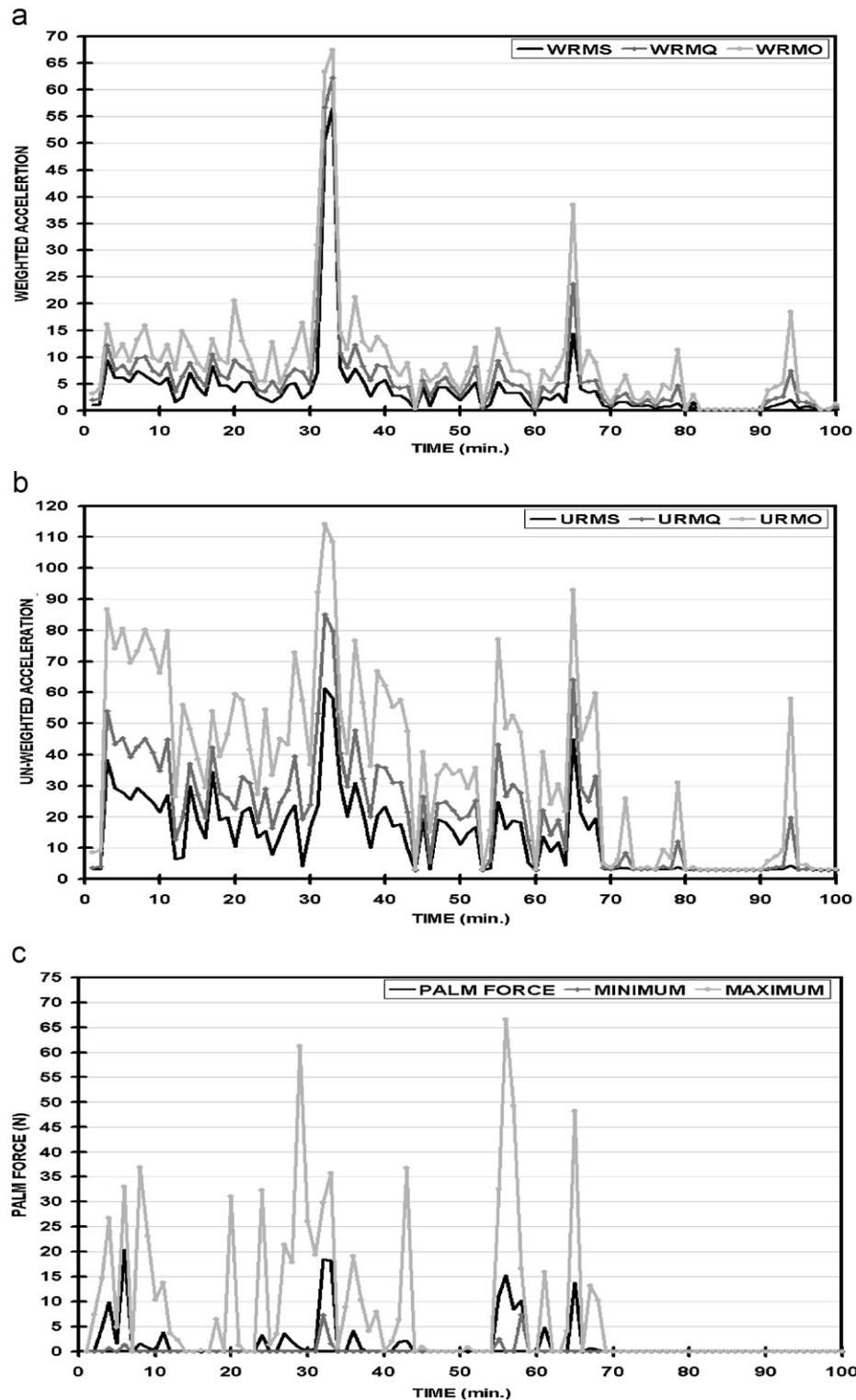


Fig. 6. Frequency-weighted, (a) and un-weighted, (b) vibration magnitudes expressed in units of m/s^2 for RMS, $m/s^{1.75}$ for RMQ, and $m/s^{1.625}$ for RMO, and time-averaged palm force exertions, (c) for 100 min of needle gun use.

vibration exposures. The ratio of the RMQ, or RMO, to the RMS gives an indication of the impulsiveness of the vibration waveform.

3. Results

For every minute the VEM system was in operation, the root-mean vibration magnitude calculations, the time-averaged palm force levels (ISO/FDIS 15230 (2007)), and the extrema of each data channel were determined and appended to a tabulated binary data file. Once exported and converted, plots of vibration magnitudes as a function of time, in increments of minutes, were easily generated. Fig. 6 shows plots of the root mean vibration magnitudes for the frequency-weighted and un-weighted data and of the palm force data logged during 100 min of actual work involving paint removal from thick metal surfaces using an in-line trigger-type needle gun. Periods of tool operation and resting are clearly visible in the plots. The vibration exposures were calculated according to Brammer and Peterson (2003) using the equation

$$E(a_i, T)_{m,r} = \left[\int_0^T [F(a_i(t))]^m dt \right]^{1/r}, \quad (2)$$

where $E(a_i, T)_{m,r}$ is the exposure occurring during the data-logged time, T , to a stimulus function that has been frequency-weighted or un-weighted (i.e., $i = W, U$), to equate the hazard at different frequencies, $F(a_i(t))$. For the needle gun example presented, the left column of Table 1 shows the vibration exposures calculated using this equation.

As previously noted, the VEM system had an electronic noise level that was inherent to each of the three data channels. With a typical sensitivity of 1 mV per 1 m/s² for the PCB accelerometers, the maximum recorded RMS noise levels for an un-stimulated accelerometer were observed to be as much as 3.25 m/s² for the un-weighted channel and 0.5 m/s² for the weighted channel. For the palm force channel, RMS noise levels were observed to be very close to 0 N (i.e., 0.003 mN) once the regression model from the subject-based force sensor calibration was applied to the data.

Since the vibration exposure is a time-weighted calculation, the inclusion of the root mean vibration magnitudes

calculated during periods of electronic noise (e.g., an un-stimulated accelerometer) were observed to directly influence the resulting exposure. The magnitude of the electronic noise was also observed to vary slightly from trial to trial for each VEM unit. Thus, the removal of the electronic noise logged by the system was required to maintain accuracy by retaining only the meaningful vibration magnitudes. The right column of Table 1 shows the calculated exposure after the removal of the vibration magnitudes biased by the electronic noise and demonstrates its influence on the exposure levels, which is relatively small. After the noise removal for this data set, the temporal nature of the exposure equations only affected the outcome of the RMS exposure levels at two significant digits, and four and six significant digits for the RMQ and RMO levels respectively.

3.1. Managing vibration levels biased by electronic noise

Typical tool-use patterns throughout long-duration work tasks or cycles are not continuous, but are intermittent with frequent pauses in tool operation from tool changes or rest breaks. Data logging over long durations inevitably produces an abundance of data points at which there was no exposure to vibration (a data point is defined as 1 min of data-logged results) and were observed to occasionally outnumber the exposed data points. These dormant data points were used to determine the noise levels of the individual channels. Once the data-logging trial was completed and before calculating the vibration exposures, the vibration magnitudes (i.e., dormant data points) that were recorded as a direct result of the electronic noise were removed from each channel individually using a histogram protocol written in LabVIEW (National Instruments, Austin, TX). A histogram was generated in order to tabulate the number of vibration exposure occurrences according to categorized values, or bins, throughout the data-logging period. The categorized values were determined by fixing the initial bin value of the histogram to the minimum acceleration recorded for that channel and establishing the subsequent bins in non-overlapping, adjacent increments of 0.1 m/s² from the minimum. The span of each bin was fixed to 0.0999 m/s² and was centered about the bin value and included the lower boundary of the bin but not the upper boundary, which was included as the lower boundary of the next consecutive bin. Starting with the initial bin, the bin value with the maximum number of occurrences was identified as the principal noise value for that recording and the cutoff noise value was defined to be 0.2 m/s², or two bins, above the principal value.

The histogram for the un-weighted acceleration recorded during paint removal using a needle gun is presented in Fig. 7, from which the cutoff noise value was determined to be 3.18 m/s² with a principal noise value of 2.98 m/s². This noise is clearly seen during the period of inactivity occurring during the 80–90 min time segment in Fig. 6b), yielding a total of 30 min of recorded vibration magnitudes

Table 1
Calculated vibration exposures for the duration of the VEM measurement

	Exposure before noise removal	Exposure after noise removal
Un-weighted RMS (m/s ²)	18.08	18.00
Un-weighted RMQ (m/s ^{1.75})	37.05	37.05
Un-weighted RMO (m/s ^{1.625})	72.26	72.26
Weighted RMS (m/s ²)	8.47	8.46
Weighted RMQ (m/s ^{1.75})	22.44	22.44
Weighted RMO (m/s ^{1.625})	40.19	40.19

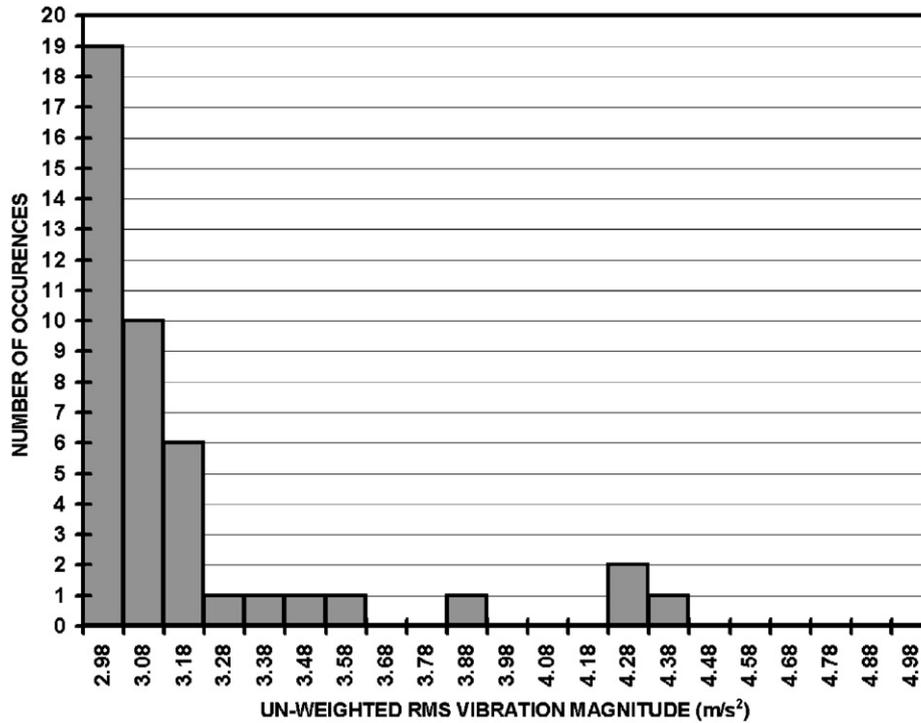


Fig. 7. Noise level histogram.

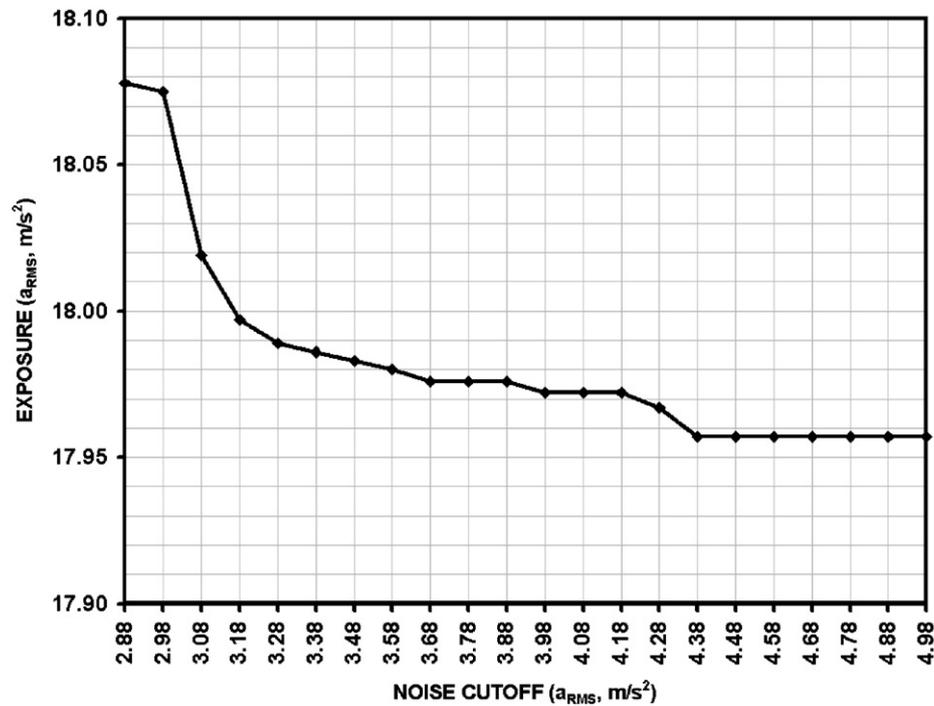


Fig. 8. Exposure as a function of the selected noise cutoff value.

less than the 3.18 m/s² cutoff value throughout the 100 min of needle gunning.

The influence of the selected cutoff noise value on the calculation of the vibration exposure was investigated (Fig. 8) and showed very little change in the exposure calculations for cutoff values selected in 0.1 m/s² incre-

ments from the absolute minimum recorded vibration magnitude, 2.88 m/s², up to 5 m/s². Different bin sizes (e.g., 0.01, 0.2, 0.5, and 1.0 m/s²) and cutoff values (e.g., 1, 5, and 20 bins above the principal value) were also investigated and generated no significant changes in the final calculation of the exposure.

4. Discussion

During the field trials, the VEM system box was placed in a nylon holster and secured to each subject using a nylon belt. Once worn by the subject, the holster was slid along the length of the belt to an optimal location that did not interfere with the work process(es) and jeopardize the operation of the VEM system. The positioning of the box depended upon the nature of the subject's work and the holster's ability to slide along the belt allowed the user to make adjustments throughout the day when needed. The holster and belt were observed to fit comfortably under all types of garments including jackets, coveralls, leather aprons, and protective wraps worn during welding. In cases where work was performed in a confined or extremely narrow space, the subject was instructed to remove the adjustable belt and holster and fasten it to their thigh.

Because the Tattletale Model 8v2 was originally designed for simple applications of remote monitoring using low-resolution signals from sensors such as thermometers, barometers, humidistats, and speedometers sampled at very low frequencies, it had to be adapted for use as a high-frequency, 8-h, data collection and processing system by efficiently managing the data storage limitations and the power consumption of the microprocessor. Recent developments in the Tattletale's technology allow it to be interfaced with a 2 GB flash memory card. This option was not available at the time the system was constructed and imposed the limitation of retaining only calculated values and not waveforms. Expanding the memory capabilities of the VEM system would permit the collection of waveforms that can be used to determine the frequency content as well as the exposure levels.

The VEM system was observed to record electronic noise levels that would yield false RMS vibration magnitudes up to 3.25 m/s^2 un-weighted and 0.5 m/s^2 weighted resulting in miscalculations of exposure, which should be, in actuality, close to 0 m/s^2 . Actual vibration magnitudes occurring below the estimated noise cutoffs were undoubtedly omitted but are of no consequence when modeling long-duration vibration exposures for assessment by current occupational exposure standards. It should be noted that this limitation would not be corrected by collecting raw waveforms using the VEM system, since these noise levels are inherent to the Tattletale unit and the custom electronic circuitry.

Palm force measurements may be compromised if the palm adapter, which only measures force at a single point and is attached to the hand rather than the tool, loses contact with the tool handle, especially if the work process, or tool, does not require a whole-handed grip. Substantial rolling of the palm adapter in the subject's hand may also compromise this measurement as well as the acceleration measurements. The orientation of the palm adapter was not typically in line with the push/pull forces associated with most tools (see Fig. 2) and the palm force measurement was not assumed to be direct component of those

forces. However, tools that have excessive torques about the y_h -axis (Fig. 2) may influence the measurement. The extents of these compromises that may occur in practice remain to be established.

Since the palm adapter design was limited to a single-point force measurement, continuous palm force measurements were not always assured and were dependent on the size and the design of the tool handle, the subject's gripping technique, and the changes in grip that occurred throughout the 15-s data collection period. This phenomenon can be seen in Fig. 6 where values for the measured palm forces are at zero while the corresponding weighted and un-weighted RMS accelerations are substantial.

According to the manufacturer, the resolution of the FSR is typically $\pm 0.5\%$ of full scale with a repeatability of $\pm 5.0\%$ of established nominal resistance. The FSRs have a non-linear performance, as indicated in Section 2.3, and are commonly known to exhibit a hysteresis effect, especially throughout repeated use and excessive wear. The extent of this effect on the collected data remains to be established.

The measurement of the coupling forces between hand and tool are an important component when modeling vibration exposures. Although the implications of this particular form of a long-duration force measurement are not yet completely understood, it may provide a means to adjust or categorize vibration exposures by inter-relating the vibration magnitude with the magnitude of the coupling force.

The intention of this paper is to introduce the VEM system and only one tool was presented to show validation and efficacy. The presentation of the data analysis and interpretation of several tools and work tasks for a large-scale, multi-cohort study involving 127 subjects in forestry, truck manufacturing, and ship building (Cherniack et al., 2006) is reserved for subsequent publications.

In summary, the published literature demonstrates that there are inconsistencies between industrial tool vibration abatement practices and observed cases of HAVS. Instrumented field measurements are necessary to authenticate exposure magnitudes and durations and are becoming increasingly significant within aspects of epidemiologic studies of neuromuscular risk in the occupational setting. The VEM system offers an improved device to more accurately characterize hand–arm vibration exposures and can assist in modeling exposure–response relationships in vibration-intensive work environments.

5. Conclusions

A small, highly portable, and inexpensive data-logging system, including a palm-mounted adapter containing an accelerometer and a force sensor, has been developed to more accurately record user-specific tool-operating times, vibration magnitudes, and palm force levels throughout all, or a representative part, of an 8-h workday. It has proved to be cost-effective, robust, and flexible and can be applied

across a wide range of occupations and occupational settings involving exposures to vibration.

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