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The Effect of a Mechanical Arm System on Portable Grinder Vibration Emissions

Thomas W. McDowell*, Daniel E. Welcome, Christopher Warren, Xueyan S. Xu and Ren G. Dong

Health Effects Laboratory Division, National Institute for Occupational Safety and Health (NIOSH), 1095 Willowdale Road, Morgantown, WV 26505, USA

*Author to whom correspondence should be addressed. Tel: +1-304-285-6337; fax: +1-304-285-6265; e-mail: TMcDowell@cdc.gov

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ABSTRACT

Mechanical arm systems are commonly used to support powered hand tools to alleviate ergonomic stressors related to the development of workplace musculoskeletal disorders. However, the use of these systems can increase exposure times to other potentially harmful agents such as hand-transmitted vibration. To examine how these tool support systems affect tool vibration, the primary objectives of this study were to characterize the vibration emissions of typical portable pneumatic grinders used for surface grinding with and without a mechanical arm support system at a workplace and to estimate the potential risk of the increased vibration exposure time afforded by the use of these mechanical arm systems. This study also developed a laboratory-based simulated grinding task based on the ISO 28927-1 (2009) standard for assessing grinder vibrations; the simulated grinding vibrations were compared with those measured during actual workplace grinder operations. The results of this study demonstrate that use of the mechanical arm may provide a health benefit by reducing the forces required to lift and maneuver the tools and by decreasing hand-transmitted vibration exposure. However, the arm does not substantially change the basic characteristics of grinder vibration spectra. The mechanical arm reduced the average frequency-weighted acceleration by about 24% in the workplace and by about 7% in the laboratory. Because use of the mechanical arm system can increase daily time-on-task by 50% or more, the use of such systems may actually increase daily time-weighted hand-transmitted vibration exposures in some cases. The laboratory acceleration measurements were substantially lower than the workplace measurements, and the laboratory tool rankings based on acceleration were considerably different than those from the workplace. Thus, it is doubtful that ISO 28927-1 is useful for estimating workplace grinder vibration exposures or for predicting workplace grinder acceleration rank orders.

KEYWORDS: exposure estimation; grinding; HAVS; musculoskeletal injury; portable grinders; risk assessment; vibration

INTRODUCTION

As reported by the US Bureau of Labor Statistics, injuries resulting from repetitive motions account for longer work absences than any other category of occupational event or exposure (BLS, 2009). According to that report, repetitive use of tools accounts for about 12% of those lost work time incidents. Specifically, prolonged use of power tools has long been associated

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with workplace injuries and musculoskeletal disorders (MSDs) in the back, neck, shoulders, arms, and hands (NIOSH, 1997; Sesto *et al.*, 2004; Chourasia *et al.*, 2009).

Materials handling manipulators such as articulated mechanical arms and hoists have been used to alleviate ergonomic stressors related to the development of workplace MSDs (Resnick and Chaffin, 1997; Chaffin *et al.*, 1999; Nussbaum *et al.*, 2000), and some of these devices and techniques have been adapted for use with powered hand tools. In recent years, the US Navy has been evaluating mechanical arm systems at their shipyards in efforts to increase productivity and to relieve some of the stressors associated with the use of heavy powered hand tools. During these early trials, it was observed that mechanical arms delayed the onset of fatigue during power tool use, and in many cases increased the daily time-on-task by 50% or more (Mattern *et al.*, 2013). In turn, such increases in tool 'trigger time' naturally increase the time that tool operators are exposed to other potentially harmful agents associated with these work tasks such as respirable dust, noise, and hand-transmitted vibration (HTV). Thus, use of these techniques may mitigate some exposures while exacerbating others.

It has been established that prolonged, repeated exposures to HTV are associated with the development of hand-arm vibration syndrome (HAVS) (Gemne and Taylor, 1983). While the mechanical arm system shows much promise for mitigating external load stressors related to power tool use, the system has not been optimized to reduce HTV exposures. Other than increasing exposure times for HTV, the effect of these tool support systems on the vibration frequency spectra and acceleration magnitude has not been reported. To begin to explore this issue, the primary objectives of this study were to (i) characterize the vibration emissions of typical portable pneumatic grinders used for surface grinding with and without the mechanical arm tool support system at a workplace and (ii) estimate the potential risk of the increased vibration exposure time afforded by the use of the mechanical arm system. In addition, this study also involved the development of a laboratory-based simulated grinding task based on the ISO standard for assessing grinder vibrations (ISO 28927-1 (2009). A secondary objective was to compare the laboratory-based simulated grinding vibration emissions with those measured during actual workplace grinder operations.

METHODS

Grinders and grinding wheels

Four portable pneumatic grinder models were included in the study to evaluate the effects of the mechanical arm on grinder vibration; each grinder model is shown in Fig. 1, while more details about the tools are presented in Table 1. Three of the grinder models (A, C, and D) were vertical grinders and one was an angle grinder (model B). Grinder model B incorporates an auto-balancing system to reduce emitted vibrations, while model D features a polyurethane elastomer for this purpose; the literature supplied with grinder models A and C makes no mention of anti-vibration features.

There were two major components to this study; the first phase of the study involved actual workplace grinding vibration assessments, while the second laboratory-based phase focused on simulated grinding. Due to the limited time allotted for the workplace research, only one sample of each grinder model was used. Two samples of each grinder model were used in the laboratory evaluations. In the workplace, two of the vertical grinders were outfitted with Type 11 flaring-cup abrasive wheels; the other two grinders were equipped with Type 27 depressed-center abrasive wheels (refer to Table 1). To simulate grinding in the laboratory trials, the abrasive wheels were replaced with unbalanced aluminum test wheels with the same shapes and sizes as the abrasive grinding wheels as is prescribed in ISO 28927-1 (2009). Samples of the grinding wheels and the unbalanced aluminum test wheels are also shown in Fig. 1.

In both the workplace and laboratory phases, the tools were supplied by large-capacity, regulated air supplies with air pressure and flow rates set in accordance with the tool manufacturers' specifications. All tools were lubricated according to the specifications.

Grip force monitoring instrumented handle

It is well known that changes in the applied hand forces can influence the vibration transmitted to the hands of tool operators (Griffin, 1990; Aldien *et al.*, 2005; Marcotte *et al.*, 2005; Dong *et al.*, 2008a). To minimize the influence of this variable on the vibration measurements, the applied grip force was monitored and

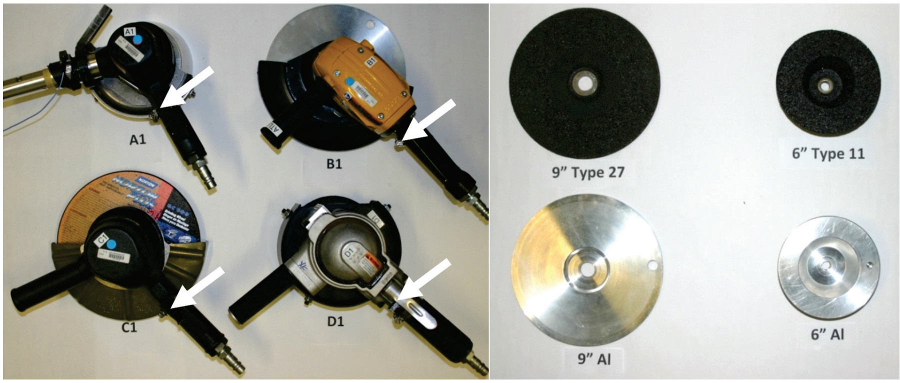

Figure 1 The four grinder models and grinding wheels used in the study. Each of the tools is shown with their accelerometers mounted on the right handle (arrows show locations); the accelerometer used for the left-handle acceleration measurements on all grinders is shown mounted on the instrumented handle installed on Tool A1. In the workplace trials, the grinders were equipped with high-grade abrasive wheels (Type 27 disks or Type 11 flaring cups). In the lab, the abrasive wheels were replaced with unbalanced aluminum disks and cups.

Table 1. Descriptions of the grinders and abrasive wheel types used in the evaluations. Tools A1, B1, C1, and D1 were used in all conditions. Tools A2–D2 were used only in the laboratory evaluations. In the laboratory trials, the abrasive wheels were replaced with unbalanced aluminum test wheels with the same dimensions as the abrasive wheels

Tool ID	Manufacturer	Model	Description	Weight (kg)	Abrasive wheel
A1, A2	Ingersoll-Rand	88V60S106	Vertical grinder	6.1	Type 11: 150 mm
B1, B2	Atlas Copco	GTG40S060-927	Turbine angle grinder	5.4	Type 27: 230 mm
C1, C2	Ingersoll-Rand	99V60P109	Vertical grinder	6.3	Type 27: 230 mm
D1, D2	Honsa	HTVG37-S-6	Vertical grinder	5.4	Type 11: 150 mm

controlled in the laboratory phase of this study. To help determine an appropriate target grip force for the lab studies, the applied grip force was recorded for each trial during the workplace grinder vibration evaluations. For this purpose, an instrumented aluminum handle (shown in Fig. 2) was developed for this study to measure the applied grip forces at the left hand of the grinder operator. During the study, the left tool handles were removed from each grinder, and this instrumented handle was installed in place of the factory-installed handle prior to a set of trials for each tool/test condition combination. A tri-axial accelerometer was mounted on the instrumented handle in the same fashion as the one on the right tool handle. The instrumented handle, including the accelerometer and force sensors, weighed ~0.5 kg. To provide a consistent interface between the mechanical arm system and each grinder, the instrumented handle also served as the attachment point for the tool support system for each tool (Fig. 3).

The instrumented handle was of a two-piece construction—the main body and the measuring cap. To quantify the applied grip force, two single-axis force sensors (Kistler 9212) were sandwiched between these two parts of the split handle; one force sensor was installed at each end of the measuring cap. The signals from the two force sensors were fed to a National Instruments data acquisition card and module (NI CDAQ 9191; NI 9215); the grip force data were sampled at a rate of 500 Hz. The two grip force signals were averaged, summed, displayed, and recorded via a computer program developed in-house using National Instruments software (LabVIEW 2012). In the laboratory phase of the study, the grip force was displayed as a large virtual dial gauge

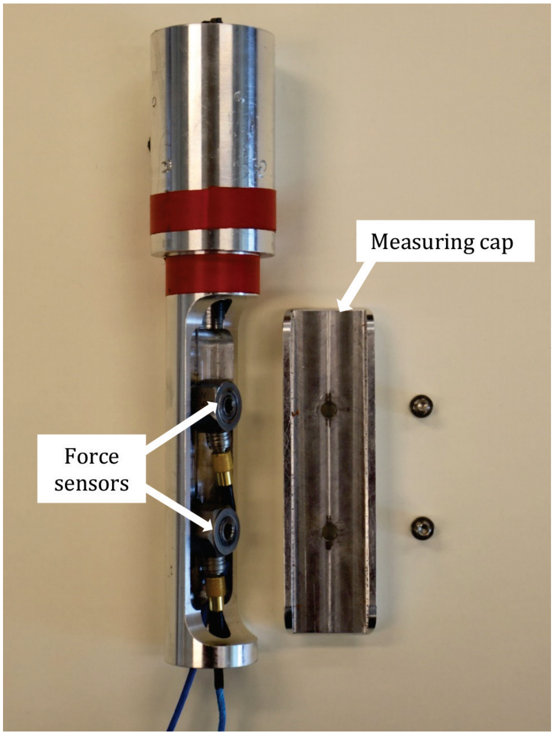

Figure 2 The left handle of each grinder was removed and replaced with this two-piece instrumented handle. The instrumented handle was used on all grinders in both support conditions in the lab and in the workplace trials. To measure the grip force, two single-axis force sensors were sandwiched between the two parts of the split handle; one force sensor was installed at each end of the measuring cap. The collar of the instrumented handle served as the attachment point for the mechanical arm system and an accelerometer (see Fig. 3).

on a computer monitor placed in front of the tool operator. The grip force display was refreshed at a rate of 5 Hz. In the shipyard study, the grinder operators were not provided with grip force feedback.

Because the maximum grip force is observed at the fingertips (Dong *et al.*, 2008b; Wimer *et al.*, 2009), it is desirable that the fingertips of the grinder operator be positioned near the middle of the measuring cap during each tool operation; to achieve this, the handle was rotated to accommodate each operator and task/posture during the lab and shipyard studies.

Mechanical arm tool support system

The mechanical arm used in this study (Equipois® zeroG4®, double link) had a maximum payload rating of 16.4kg. This mechanical arm system consists of four primary

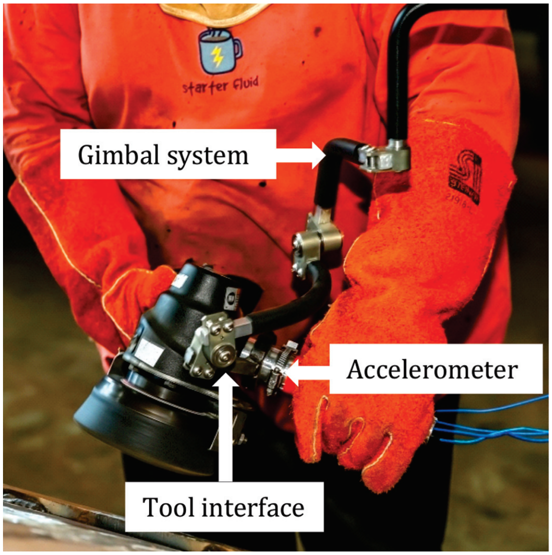

Figure 3 The mechanical arm's gimbal system was attached to the collar of the instrumented handle near the body of the grinder via the tool interface. An accelerometer can be seen mounted on the handle with a mounting block and hose clamp between the tool interface and the thenar region of the tool operator's gloved hand. A second accelerometer (obscured in the photo) was similarly attached to the right tool handle for simultaneous acceleration data collection (see Fig. 1).

subsystems: (i) the articulated arm with adjustable tensioners, (ii) the gimbal system with segments that can be positioned in multiple configurations to allow for angular freedom of motion for a specific task, (iii) the tool interface that can be customized to fit a specific tool body or handle; and (iv) the mobile mounting system. In preparation for this study, the articulated arm and gimbal systems were adjusted for proper tension and freedom of motion required for the study's three prescribed tasks. The tool interface was customized to fit the cylindrical instrumented tool handle that was used on all grinders and all tasks throughout the study. The gimbal and tool interface arrangements are shown in Fig. 3. In both the laboratory and workplace trials, the mechanical arm system was mounted on a mobile stand (Equipois® Quad Stand) equipped with counterweights, lockable wheels, and a manually operated ratcheting hoist for adjusting the arm height via a vertical track-mounted cable and pulley system.

Acceleration data collection system

In both the lab and the workplace, the grinder vibration emissions were evaluated by measuring the acceleration simultaneously at both tool handles in close proximity to where the vibration enters the operator's hands in accordance with ISO 5349-2, 2001 (ISO, 2001b) and ANSI S2.70–2006 (ANSI, 2006). To examine how the frequency weighting affects the results as is recommended in NIOSH Publication #89–106 (NIOSH, 1989), the grinder vibrations were evaluated based on band-limited unweighted acceleration as well as by frequency-weighted acceleration.

Figure 1 shows accelerometers mounted on the right handles of each of the four tool models. Figs 1 and 3 also show the accelerometer mounted on the instrumented handle that was installed in place of the left handle on each grinder during the study. All grinder vibration measurements were collected via PCB Model 356B11 piezoelectric tri-axial accelerometers. The accelerometers were installed on mounting blocks and secured to the handles with hose clamps.

Tri-axial vibration data were collected via a portable six-channel B&K PULSE system (Brüel & Kjær, Input/Output Module Type 3032A). The vibration data collected from this system were expressed as the root-mean-square (r.m.s.) values of the accelerations in the one-third octave frequency bands, with center frequencies from 6.3 to 1250 Hz. The sampling rate of the B & K system is 2.56 times the highest frequency sampled, or in this case, 3200 Hz. Both time-history data and frequency spectrum were recorded. The vector sum or 'total' values of the unweighted r.m.s. accelerations were computed using the following formula:

$$a_h = \sqrt{a_{hx}^2 + a_{hy}^2 + a_{hz}^2} \qquad (1)$$

where a_h is the unweighted root-sum-of-squares total value, and a_{hx}, a_{hy}, and a_{hz}, are the unweighted r.m.s. acceleration values for the *x*-, *y*-, and *z*-axes, respectively.

To determine the ISO frequency-weighted acceleration values for each axis, an Excel spreadsheet was used to apply the frequency-weighting factors defined in ISO 5349-1 (ISO, 2001a):

$$a_{hw} = \sqrt{\sum_{j=1}^{24} (w_j a_{h,j})^2} \qquad (2)$$

where a_{hw} is the single-axis frequency-weighted r.m.s. acceleration, w_j is the weighting factor for the *j*th one-third octave band as provided in Table 2 of the standard, and $a_{h,j}$ is the acceleration measured in the *j*th one-third octave band. In this process, the 24 one-third octave frequency band r.m.s. accelerations are multiplied by their respective weighting factors, and the resultant weighted r.m.s. accelerations are determined for each axis.

Then, as was done with the unweighted acceleration, the total ISO frequency-weighted values are computed using

$$a_{hv} = \sqrt{a_{hwx}^2 + a_{hwy}^2 + a_{hwz}^2} \qquad (3)$$

where a_{hv} is the ISO frequency-weighted root-sum-of-squares total value, and a_{hwx}, a_{hwy}, and a_{hwz} are the ISO frequency-weighted r.m.s. acceleration values for the *x*-, *y*-, and *z*-axes, respectively.

Workplace grinder vibration assessments

The first phase of this study involved the workplace evaluations of pneumatic grinder vibrations. The vibration assessments were conducted at a large US naval shipyard over a 2-day period. Four experienced grinder operators performed typical grinding tasks over four data collection sessions; each day was divided into a morning session and an afternoon session; one grinder operator conducted the work per session. Two work tasks were selected for the shipyard evaluations; the first workstation was set up for vertical surface grinding mild steel, while the second workstation was configured for horizontal grinding. Both tasks involved removing metal from steel bars that were welded to the surface of the steel structure; the steel bars were ~40 mm wide with a thickness of ~15 mm. Figure 4b,c shows an operator performing each shipyard task with a grinder mounted on the mechanical arm. The grinder vibrations were also measured while they were operated using the same postures without the support of the mechanical arm system. The four grinders shown in Fig. 1 were used in the shipyard evaluations. Each operator completed five data collection trials with each tool/task/support condition combination. The abrasive grinding wheels were discarded and replaced with brand new ones after each five-trial data collection period. During a data collection session, the tool operator completed an 80-trial test matrix (4 tools × 2 tasks × 2 support conditions × 5 trials = 80 trials). The support condition alternated between five-trial data sets, while the order of the tools was randomized for each tool operator. The operators completed all 40 trials at one workstation before moving to the second workstation; two of the operators

Table 2. Unweighted and frequency-weighted acceleration means and coefficients of variation (C_V = SD/mean) for the left tool handle for each grinder, workstation, and support condition combination

	Simulated grinding (lab)				Vertical grinding (workplace)				Horizontal grinding (workplace)			
	Unsupported		Supported		Unsupported		Supported		Unsupported		Supported	
Tool	Unweighted acceleration (m s^{-2})	C_V	Unweighted acceleration (m s^{-2})	C_V	Unweighted acceleration (m s^{-2})	C_V	Unweighted acceleration (m s^{-2})	C_V	Unweighted acceleration (m s^{-2})	C_V	Unweighted acceleration (m s^{-2})	C_V
A1	23.6	0.12	12.4	0.06	130.9	0.14	122.3	0.12	153.6	0.09	91.7	0.16
A2	29.3	0.10	20.6	0.10								
B1	32.6	0.15	22.5	0.13	134.9	0.14	190.0	0.14	148.7	0.11	142.5	0.12
B2	20.9	0.04	20.1	0.06								
C1	39.0	0.13	23.1	0.07	106.9	0.09	87.1	0.18	111.8	0.18	108.7	0.13
C2	39.9	0.12	19.6	0.06								
D1	35.7	0.05	27.6	0.03	91.1	0.09	61.5	0.13	92.8	0.07	59.3	0.13
D2	39.3	0.06	28.2	0.03								
Tool	Weighted acceleration (m s^{-2})	C_V	Weighted acceleration (m s^{-2})	C_V	Weighted acceleration (m s^{-2})	C_V	Weighted acceleration (m s^{-2})	C_V	Weighted acceleration (m s^{-2})	C_V	Weighted acceleration (m s^{-2})	C_V
A1	1.2	0.10	1.2	0.10	5.1	0.16	4.5	0.12	6.6	0.17	4.6	0.10
A2	1.7	0.11	1.6	0.10								
B1	4.2	0.08	3.2	0.10	5.6	0.06	5.7	0.12	6.5	0.16	4.6	0.11
B2	3.0	0.07	3.0	0.05								
C1	2.6	0.10	2.7	0.12	3.0	0.11	3.2	0.16	2.6	0.10	2.8	0.13
C2	2.3	0.09	2.0	0.11								
D1	3.4	0.02	3.2	0.01	8.0	0.11	4.7	0.13	8.2	0.15	4.4	0.15
D2	3.3	0.02	3.3	0.02								

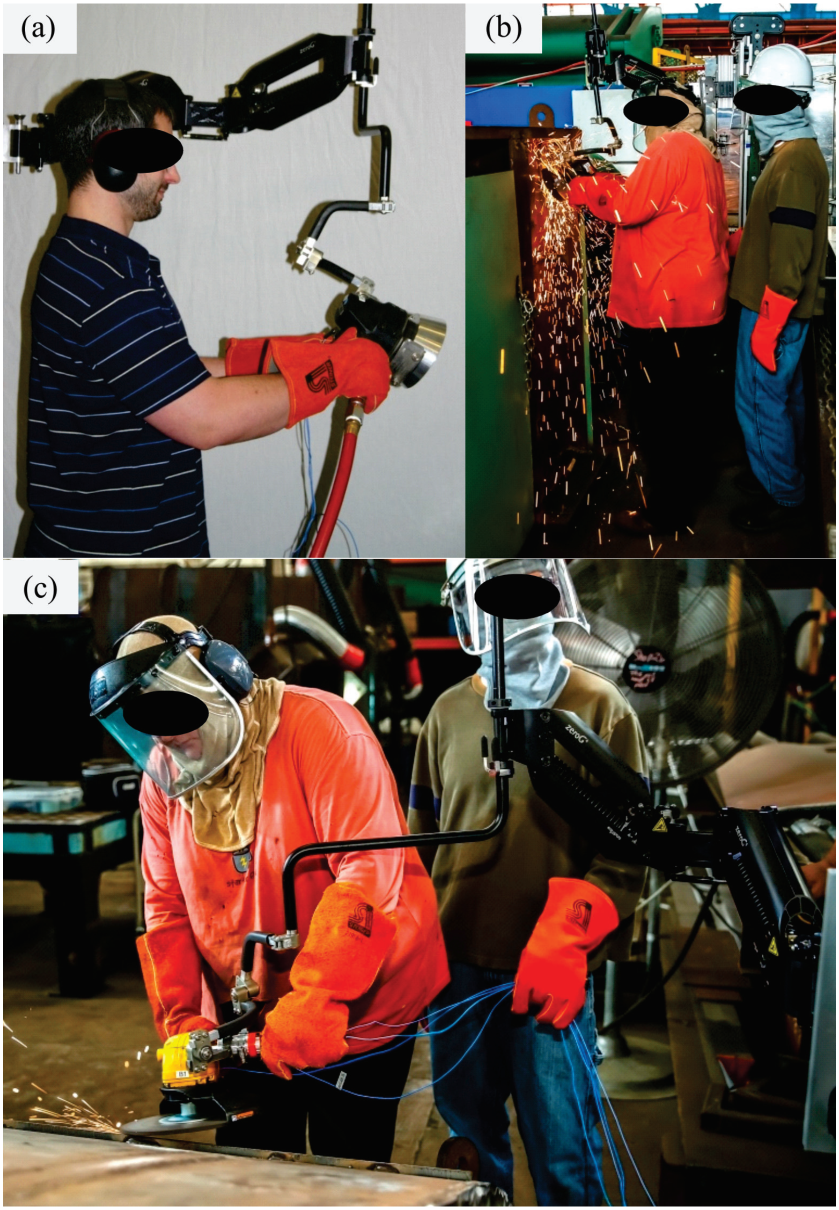

Figure 4 The three workstations used in the evaluations: (a) simulated vertical grinding using unbalanced test wheels as prescribed by ISO 28927-1 (2009); (b) vertical surface grinding mild steel at about shoulder height; and (c) horizontal surface grinding mild steel at about thigh height. The grinders are shown in the supported condition; vibration data were also collected in the unsupported condition using the same postures (not shown).

started with the vertical grinding task, and the other two began with the horizontal grinding task.

Prior to beginning a data collection session, the grinder operator was briefed on the testing procedure, and was advised to operate the grinders using the same postures, motions, and applied forces as they normally would to complete the grinding tasks. Before a set of trials began, a NIOSH engineer prepared the designated grinder for operation and data collection by installing the instrumented handle and, in the case of the supported trials, attaching the tool interface to the gimbal of the mechanical arm system. The engineer handed the prepared grinder to the grinder operator who got into position to complete the first data collection trial. A trial consisted of grinding the exterior surface of a welded steel structure for 10 s. At the 'START' command given by the NIOSH investigator, the grinder operator fully depressed the grinder's paddle actuator on the right handle to start the grinder, and then pressed the rotating grinding wheel onto the surface of the steel structure and proceeded to use a rhythmic, elliptical side-to-side, fore-aft, or up-down motion, depending on the work piece configuration. Data collection commenced once the grip force and motion of the grinder were observed to be stable—usually a second or two after the abrasive wheel made initial contact with the steel surface. Data collection lasted exactly 10 s per trial. At the end of the 10-s data collection period, a NIOSH engineer tapped the grinder operator on the shoulder to indicate that the trial was over. The tool operator then ceased grinding and released the paddle actuator and rested for several seconds while the investigator saved the grip force and acceleration data files. Once the files were saved, the grinder operator was prompted to get ready for the next trial. This process was repeated until the operator completed five consecutive trials with the designated grinder/support condition combination. At the end of the fifth trial, the grinder operator handed the grinder back to the engineer who then prepared for the next grinder/support condition in the test sequence. This progression continued until all 40 trials were completed for that workstation. Then, the mechanical arm system and tools were relocated to the second workstation where the 40-trial process was repeated with the grinders presented to the operator in a different, predetermined randomized sequence.

It should be noted that while the grip force was recorded for each shipyard grinding trial, the grinder operators were not provided with feedback of their applied grip forces during the tool operations. In fact, the grinder operators were not informed that their grip forces were being measured in the shipyard phase of the study.

Laboratory simulated grinding vibration assessments

Following the shipyard evaluations, the grinders, mechanical arm system, and data collection equipment were transported back to the NIOSH hand-arm vibration laboratory. Six locally recruited males served as grinder operators during the laboratory phase of the study. The test subjects were experienced tool operators, but they were novice grinder operators. With informed consent, the recruited tool operators followed a protocol based on the International Organization for Standardization (ISO) standard for laboratory-based assessments of the vibration emissions of angle and vertical grinders (ISO 28927-1, 2009). In lieu of actual grinding, the standardized procedure employs unbalanced test wheels to simulate a grinding task. The laboratory study protocol was reviewed and approved by the NIOSH Human Subjects Review Board. Each grinder operator underwent a familiarization period with the grinder operation, the simulated grinding task, and the grip force monitoring system. Each operator performed a few practice trials. Once comfortable with the procedure, the operator began the series of data collection trials similar to the test matrix employed in the shipyard evaluations.

In addition to the four grinders used in the shipyard trials, four grinders of the same makes and models were added to the test matrix (Table 1). However, because there was only one work task in the laboratory sessions, the size of the test matrix was the same as that in the shipyard. (8 tools × 1 task × 2 support conditions × 5 trials = 80 trials) In the lab, the abrasive grinding wheels were replaced with unbalanced aluminum test wheels fabricated to the specifications prescribed in ISO 28927-1 (2009). Basically, the test wheels are fabricated from aluminum alloy with the same dimensions as typical abrasive grinding wheels. Holes are then drilled to the specifications prescribed in the standard. The material removed from one side of the test wheel causes an imbalance as the test wheel rotates. According to the standard, the unbalanced test wheels are designed to produce grinder vibrations that are representative of many typical workplace grinding tasks.

As in the shipyard evaluations, the grinders were presented to the operators in a predetermined random order. Also like the shipyard assessments, the support condition alternated between five-trial sets. To begin a trial, the operator was instructed to hold the grinder in a comfortable position at about chest level as shown in Fig. 4a. This pose mimics the posture employed during the shipyard's vertical grinding task (Fig. 4b). Once in position, the operator was instructed to squeeze the left grinder handle and to try to maintain the grip force within the specified target range as displayed on the computer dial gauge (80 ± 20 N), and then to fully depress the paddle actuator on the right grinder handle to begin tool operation. Once the grip force was observed to be stable with the grinder operating at full speed, the NIOSH investigator initiated a 10-s data collection trial. A signal from the grip force computer display prompted the operator to rest at the end of each 10-s trial. The operator rested for at least 1 min between trials. The grinder operator completed five consecutive trials with each grinder/support condition combination. At the completion of five trials, the coefficient of variation (C_V) of the ISO frequency-weighted total value (a_{hv}) was immediately calculated for those trials. As is specified in the ISO 28927 series of standards, trials were repeated if the C_V was found to be 0.15 or greater. Vibration measurements proved to be fairly consistent as less than 10% of all trials required replication. This process continued until the operator completed the entire 80-trial test matrix. Test sessions lasted a little over 2 hours per operator.

Data analyses

Left handle vs. right handle acceleration

Two-tailed *t*-tests were performed to compare the left handle unweighted and frequency-weighted acceleration means with those of the right handle for both the shipyard and laboratory studies. Because daily vibration exposures are expected to be reported based on the highest measured acceleration values of the two hands (ANSI, 2006), this study's data analyses focused on the left-handle vibration measurements.

Ranking the grinders in terms of vibration emissions

As stated in the introduction, a secondary objective of this study was to evaluate how well the laboratory-based vibration assessments could predict which grinders would produce the lowest vibrations under actual working conditions. This evaluation was based on comparisons of the rank orders (lowest to highest) of the four grinders used in both studies. Rankings were based on left-handle unweighted and frequency-weighted accelerations measured under each task and support condition.

Shipyard study analysis of variances for acceleration and grip force

For the shipyard study, a univariate general linear model (GLM) of analysis of variance (ANOVA) for unweighted acceleration was conducted to evaluate the influence of three fixed factors: grinder (four levels), support condition (two levels), and work task (two levels). Operator was included in the statistical model as a random factor. This same ANOVA model was repeated for frequency-weighted acceleration. A similar ANOVA was conducted for grip force in the shipyard study; along with the factors listed above, grinding wheel type, and trial number were added to the statistical model.

Laboratory study ANOVAs for acceleration

For the laboratory study, the GLM ANOVA models for unweighted and frequency-weighted acceleration included grinder model (four levels), support condition (two levels), and operator as a random factor.

For both the shipyard and laboratory studies, Tukey honestly significant difference (HSD) *post hoc* pairwise comparisons were also performed to compare the grinder acceleration means. For the shipyard study, the relationship between grip force and vibration at the left handle was also explored using a Pearson correlation analysis. All statistical analyses were performed using SPSS statistical software (IBM SPSS Statistics, version 19.0). Analysis results were considered significant at the $P < 0.05$ level.

RESULTS

Left handle versus right handle acceleration

For the shipyard trials, the average unweighted acceleration measured at the left handle (114.6 m s^{-2}) was significantly higher than that for the right handle (82.8 m s^{-2}) (*t*-test, $P < 0.001$). This held true for both the supported and unsupported trials. Likewise for frequency-weighted acceleration, the left-handle average (5.0 m s^{-2}) was higher than the right handle average (3.8 m s^{-2}) (*t*-test, $P < 0.001$).

The acceleration measurements in the laboratory were considerably lower than those in the shipyard trials, and the differences between the left handle and the right handle were much smaller and practically meaningless. For unweighted acceleration, the left-handle mean was 27.2 m s^{-2}, while the right handle mean was 24.9 m s^{-2}. For frequency-weighted acceleration in the lab study, the right handle mean was actually higher than the left handle (2.9 versus 2.6 m s^{-2}).

One-third octave band frequency spectra

Each grinder's average one-third octave band frequency spectra measured at the left tool handle while the operators performed the various grinding tasks are shown in Fig. 5. As can be seen, the dominant frequency of each tool was between 80 and 100 Hz. The support condition had little effect on the frequency spectra for any of the three tasks. While the spectra for the vertical and horizontal shipyard grinding tasks are similar to each other, they show somewhat different signatures than the laboratory-based simulated grinding, especially for frequencies below 100 Hz.

Data analysis results—left handle acceleration measurements

Table 2 contains the left-handle frequency-weighted and unweighted acceleration averages for the four grinders used in both the laboratory and shipyard evaluations along with the four additional grinders used in laboratory study.

For the shipyard study, the ANOVA for unweighted acceleration revealed that grinder was the only significant factor influencing acceleration; no other factors or

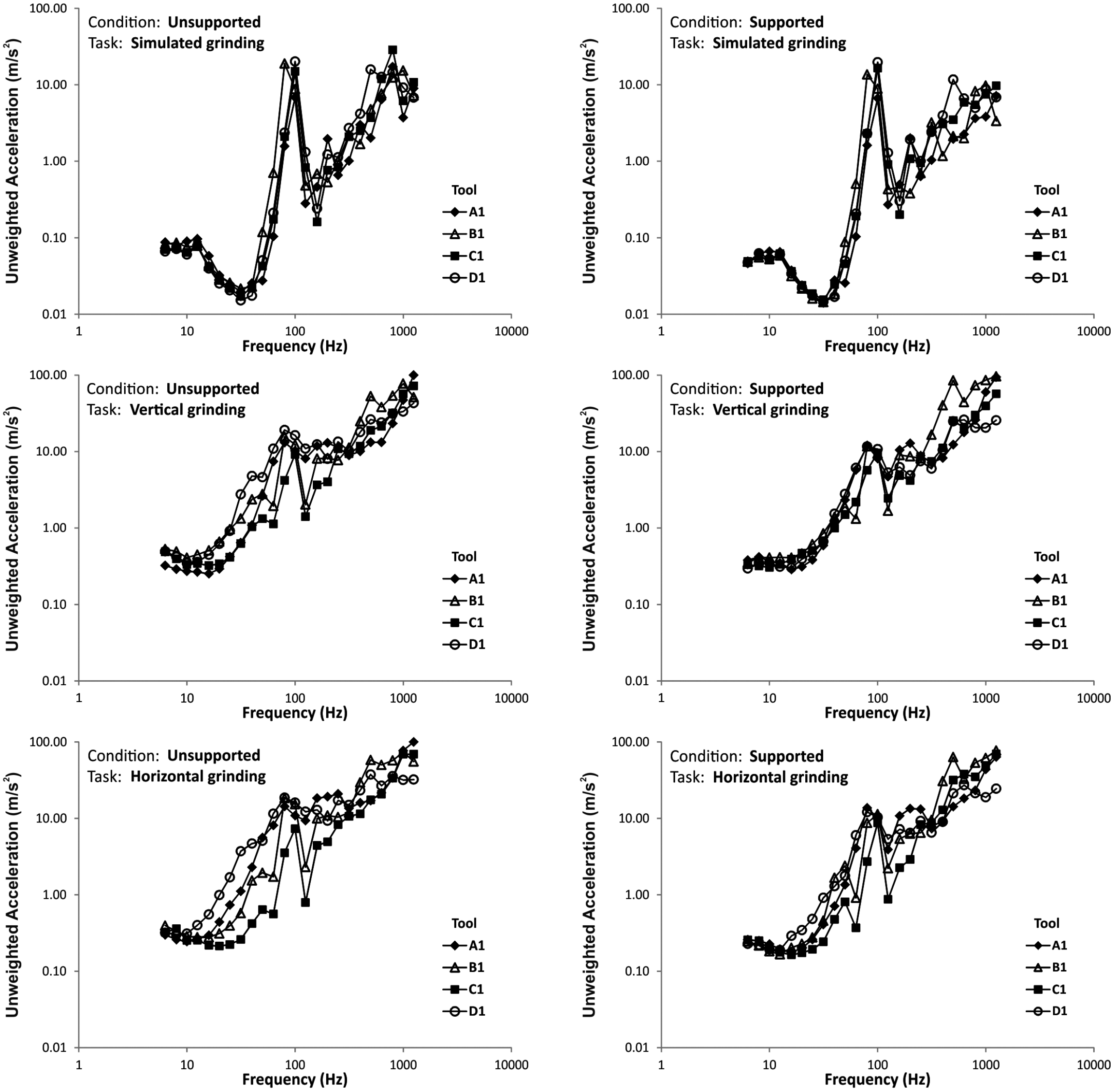

Figure 5 Average one-third octave band frequency spectra measured at the left handles of the four grinders evaluated under all conditions.

interactions were statistically significant. The ANOVA for frequency-weighted acceleration showed that grinder and support condition were both significant factors; no other factors or interactions were statistically significant. The weighted acceleration mean for the unsupported trials (5.7 m s^{-2}) was significantly higher than the mean for trials when the grinder was supported by the mechanical arm system (4.3 m s^{-2}).

The laboratory study ANOVA for unweighted acceleration revealed that grinder model, support condition, and the interaction between those two factors were all significant factors. The use of the mechanical arm reduced the unweighted acceleration by an average of 33% in the laboratory trials. While the unweighted acceleration was reduced for every tool, the extent of reduction varied by tool model ranging from about 18% for the A model grinders up to 46% for the C model tools. The ANOVA for frequency-weighted acceleration showed grinder model to be the only significant factor; the mechanical arm had little to no effect on weighted acceleration for any of the tool models.

Comparisons of the laboratory and shipyard grinder rank orders

In the laboratory trials, Tool A1 produced the lowest unweighted and frequency-weighted accelerations in both the supported and unsupported conditions. For unweighted acceleration, Tool B1 was ranked second under both support conditions, while Tool C1 had the second lowest frequency-weighted acceleration means under each support condition.

The shipyard grinder rankings were quite different. While Tool D1 was not ranked in the top two in any category in the laboratory trials, this tool ranked the best in terms of unweighted acceleration under both support conditions for both the vertical and horizontal grinding tasks. For frequency-weighted acceleration, Tool C1 was ranked the best for both tasks and support conditions.

Shipyard grip force measurements

The means for grip force measured at the left handle for each work task/support condition combination are presented in Table 3. The average grip force for the supported grinders was 82.0 N, while the average for the unsupported grinders was 59.5 N. The ANOVA for grip force revealed that the grinding wheel type and the work task/support condition interaction were the only significant factors. The average grip force (77.5 N) for the grinders equipped with the Type 27 depressed-center abrasive wheels was significantly higher than that for the Type 11 flaring-cup abrasive wheels (64.0 N). For the work task/support condition combinations, the average grip force ranged from 43.9 N for the unsupported vertical grinding trials to 104.9 N for the supported horizontal grinding trials.

The Pearson correlation analyses revealed no significant relationship between the applied grip force and left-handle acceleration ($P \geq 0.15$).

DISCUSSION

This study revealed some useful information of the effects of a mechanical arm tool support system on pneumatic grinder HTVs. Such information can be used to help assess the risk of vibration exposures of these grinders when used in conjunction with the mechanical arm. This information may also be used to improve applications of mechanical arm support systems.

The effects of the mechanical arm on handle vibration spectra and magnitudes

The results of this study demonstrate that the mechanical support arm does not substantially change the basic shapes or characteristics of the vibration spectra, as shown in Fig. 5. However, the mechanical arm system generally reduced the unweighted accelerations of all the tools in the laboratory test, as indicated in Table 2. This is because the mechanical arm coupled to a tool handle can increase the effective mass of the tool, which can reduce the acceleration under the same vibration force generated by the spinning components of the grinders. The results presented in Table 2 and Fig. 6 also demonstrate that, in many cases, the mechanical arm's influence on frequency-weighted acceleration was not substantial. This is consistent with a recent UK HSE report on the use of spring tensioners to reduce fatigue and vibration (Shanks *et al.*, 2013). The results of the present study indicate that the use of the mechanical arm did not consistently reduce the dominant vibrations of the grinders in the frequency range of 80–100 Hz. This suggests that the reductions in unweighted acceleration mostly occurred at higher frequencies (>100 Hz).

Table 3. Shipyard grip force means and coefficients of variation (C_V = SD/mean) as measured at the left tool handle for each grinder, workstation, and support condition combination

Support		Vertical grinding		Horizontal grinding	
Condition	**Grinder**	**Grip force (N)**	**C_V**	**Grip force (N)**	**C_V**
Unsupported	A1	37.8	0.28	69.6	0.20
Unsupported	B1	52.2	0.24	86.5	0.20
Unsupported	C1	45.5	0.33	84.5	0.21
Unsupported	D1	39.9	0.20	60.1	0.23
Supported	A1	49.4	0.23	95.0	0.25
Supported	B1	66.9	0.20	107.0	0.26
Supported	C1	64.4	0.23	113.1	0.12
Supported	D1	55.6	0.18	104.7	0.14

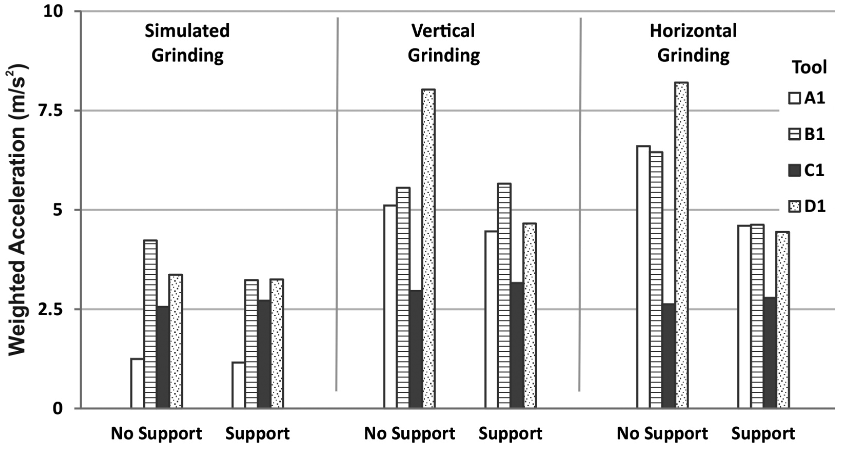

Figure 6 Frequency-weighted acceleration averages measured at the left handles of the four grinders evaluated under all conditions.

As also presented in Table 2, the vibration reductions due to the mechanical arm were not consistent across the tools in the shipyard tests. While the mechanical arm effectively reduced the frequency-weighted acceleration of Tool D1, it did not significantly reduce the unweighted acceleration of the same tool. In some cases (e.g. Tool B1 in vertical grinding), the tool generated higher acceleration when the mechanical arm was used. This may be because the tool vibrations in the shipyard operations are influenced not only by the mechanical arm but also by many other factors such as the applied feed force, working materials, grinding angles/orientation, initial grinding wheel unbalance, and grinding wheel variability (Stayner, 1996; Liljelind *et al.*, 2010; Liljelind *et al.*, 2011). These uncontrolled factors may be further affected by the use of the mechanical arm system. As many of these factors are difficult to quantify or control, it is a challenge to clearly identify all influential effects and interactions in regards to grinder vibration.

Nevertheless, the frequency-weighted acceleration magnitudes measured in the shipyard study are similar to grinder accelerations reported by the UK Health and Safety Executive (Stayner, 1996) and also by Wilhite (2007), but higher than the accelerations reported by Liljelind *et al.* (2011). It should also be noted that in the shipyard study, the grinding wheels were replaced with brand new ones after five 10-s trials. Thus, each grinder operator had their own set of fresh grinding wheels. Therefore, it is unlikely that there was enough time for the wheels to develop significant 'lobing' (uneven wear) as described in the UK HSE report (Stayner, 1996), which has been shown to lead to significant wheel unbalance and subsequent increased vibration emissions. On the other hand, Liljelind *et al.* (2011) reported reductions in vibration from grinders during the second minute of wheel use as compared to the first minute, so the present study results would not reflect this phenomenon.

Working posture was not found to be an important factor in acceleration as the averages for the workplace vertical grinding task and the horizontal grinding task were not statistically different. This finding is consistent with that of recent grinder vibration studies (Wilhite, 2007; Liljelind *et al.*, 2011).

The effects of the mechanical support arm on grinder grip force

One unexpected observation during this study was the fact that the measured grip forces in the shipyard study were higher during trials when the tool was supported by the mechanical arm. This phenomenon contradicts that previously reported (Nussbaum *et al.*, 2000). This is because the effects of the support arm on hand forces depend on the job requirements. In the reported study by Nussbaum *et al.* (2000), hand forces were measured while operators manipulated materials (boxes with handles) with and without the use of support systems. In such material transfer operations, hand forces can be obviously reduced by using support systems to counterbalance the weight of the load. In overhead or vertical grinding, a support arm can also function in a similar manner. However, in horizontal grinding, a certain contact force is required to perform the grinding task, and to a certain point, grinding productivity is likely to increase with the applied push force; the support arm actually reduces the grinding contact force by counter-balancing the weight of the grinder. As a result, additional push force is required to achieve the desired productivity. To effectively control the tool, the operator may also have to apply additional grip force in horizontal grinding operations, as indicated in Table 3. These observations suggest that the actual benefits of the support arm depend on the working conditions and job requirements. From this standpoint, the support arm may be generally more beneficial during vertical or overhead grinding than during horizontal grinding.

It should be noted that there are some uncertainties in the grip force measurements performed in this study. As shown in Fig. 2, the instrumented handle used in this study can only measure the grip force in one direction at a time. However, measured grip force generally varies with the measurement orientation (Dong *et al.*, 2008b). The hand postures and grip orientations used during horizontal grinding may be different from those in vertical grinding. This may at least partially explain why the grip force values are different in these two tasks, as indicated in Table 3. It was also observed that the fingertips of the grinder operator would sometimes stray from the optimal measurement zone (measuring cap) of the instrumented handle; this was especially true during unsupported horizontal grinding. When the support arm was installed on the handle, the support arm's gimbal system limited the operator's ability to slide the left hand along the handle, and thus the fingertips were more prone to remain centered on the grip force measuring cap during the supported trials. This suggests that the grip force measured without the supporting arm may be underestimated. Further studies with a more reliable method for measuring the grip force are required to verify the effects of the support arm on grip forces.

It should also be noted that increased hand coupling forces during horizontal grinding does not necessarily mean that the support arm is not beneficial for such operations. Horizontal grinding also requires frequent lifting of the tool during the grinding cycle. The support arm can certainly reduce these lifting forces. Furthermore, lifting and pushing involve different muscle groups; it may be easier for the human body to push than to lift. For example, while lifting generally increases the spinal load, downward pushing can reduce the spinal load. Increases in pushing and gripping during horizontal grinding may not increase overall stress or fatigue levels. This may explain why the feedback we received from the study participants was mostly positive, as every operator was pleased with the way the support arm reduced shoulder and back fatigue, especially for vertical grinding. However, one of the operators complained that the support arm reduced the operator's freedom of motion. The shipyard grinder operators also pointed out that it would be impractical to move the support arm and/or its cumbersome mobile base around the stairwells, portals, and tight quarters often encountered aboard sea vessels.

Implications for grinder vibration risk assessment

In the international standard, ISO 5349-1 (2001), a daily HTV exposure dose is weighted in terms of both daily vibration exposure time and vibration frequency; the corresponding HTV exposure level is referred to as the 8-h energy-equivalent exposure value, or A(8) value (ISO 5349-1, 2001). For an 8-h work shift, the A(8) value is calculated using frequency-weighted total acceleration (a_{hv}) and the daily exposure time (T) in hours measured at the workplace using the following formula (ISO 5349-1, 2001):

$$A(8) = a_{hv}\sqrt{\frac{T}{8}}$$

This formula indicates that while reductions to frequency-weighted acceleration afforded by the use of the mechanical arm will result in reduced A(8) values, increased exposure times allowed by such use will increase A(8) values. For example, a 20% reduction in a_{hv} would be completely offset by an increase of 50% in exposure time.

To help reduce the risk of vibration exposures, A(8) values should be controlled to the lowest feasible levels. Standards and directives have recommended or specified a daily exposure action value (DEAV) of A(8) = 2.5 m s^{-2} and a daily exposure limit value (DELV) of A(8) = 5.0 m s^{-2} (EU Directive 2002/44/EC, 2002; ANSI S2.70, 2006). According to these publications, employers are suggested or required to take actions to reduce HTV exposures if they exceed the DEAV. They further state that no worker should be exposed to HTV above the DELV. Although exposure controls may not eliminate all instances of HAVS and other disorders, it is anticipated that effective exposure control strategies can help minimize harm.

Implications for laboratory grinder assessments based on ISO 28927-1 (2009)

As shown in Fig. 5, the one-third octave band frequency spectra measured in the workplace evaluations were noticeably different than those measured in the laboratory-based simulated grinding trials. The workplace spectra feature considerably higher acceleration magnitudes in the low-frequency components than the lab-based spectra. As presented in Table 2, the unweighted acceleration averages measured in the workplace trials were two to four times those measured in the laboratory for the four grinders common to both evaluations. This was true for both the supported and unsupported conditions. Similarly, the workplace frequency-weighted acceleration averages were about twice those for the lab. Furthermore, as noted in section *Comparisons of the Laboratory and Shipyard Grinder Rank Orders*, the rankings of the grinders based on acceleration differed substantially from the lab to the shipyard. These observations indicate that the use of an unbalanced wheel for simulating surface grinding, as is standardized in ISO 28927-1 (2009), is not suitable for estimating workplace grinder HTV exposures, and may not be suitable for predicting which grinder models would be expected to produce lower vibrations in actual workplace grinding tasks.

Potential improvements to the application of the mechanical arm

The mechanical arm tool support system used in this study was not optimized to reduce HTV exposures. Thus, it is feasible that isolation and damping properties of the mechanical arm and the arm/grinder interface can be modified to allow for improved vibration reductions without sacrificing the ergonomic benefits provided by the present system design. The rated weight capacity of the mechanical arm is about 10 kg more than the heaviest grinder examined in this study. Therefore, there is considerable opportunity to add mass to the system which would naturally enhance the system's ability to reduce HTV transmissions.

CONCLUSIONS

The mechanical arm tool support system reduced the average frequency-weighted acceleration at the left grinder handles by about 24% in the shipyard study and by about 7% in the laboratory study. The reductions for unweighted acceleration averaged around 11 and 33% for the shipyard and lab, respectively. Therefore, the mechanical arm may provide a health benefit by reducing the forces required to lift and maneuver the tools and by decreasing HTV exposure. However, because it has been reported that use of the mechanical arm system can increase the daily time-on-task by

50% or more (Mattern *et al.*, 2013), the use of such systems may actually increase daily time-weighted HTV exposures. While the use of these tool support systems can alleviate some ergonomic stressors associated with the use of heavy powered hand tools, such benefits should be weighed against potential increases in other workplace exposures, including HTV.

The laboratory acceleration measurements were substantially lower than those from the shipyard study. Moreover, the laboratory tool rankings based on unweighted and frequency-weighted acceleration levels were considerably different than those from the shipyard. These results cast some doubt on the use of ISO 28927-1 (2009) for estimating workplace grinder vibration exposures or for identifying tools that could be expected to produce relatively lower vibration exposures in the workplace.

DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety & Health. The mention of trade names, commercial products, or organizations does not imply endorsement by the US Government.

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