Ann. Occup. Hyg., Vol. 57, No. 1, pp. 43–53, 2013
Published by Oxford University Press
on behalf of the British Occupational Hygiene Society [2012]
doi:10.1093/annhyg/mes049

Assessment of Hand-Transmitted Vibration Exposure from Motorized Forks Used for Beach-Cleaning Operations

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Received 8 December 2011; in final form 25 May 2012; published online 5 September 2012

Motorized vibrating manure forks were used in beach-cleaning operations following the massive Deepwater Horizon oil spill in the Gulf of Mexico during the summer of 2010.

Objectives: The objectives of this study were to characterize the vibration emissions of these motorized forks and to provide a first approximation of hand-transmitted vibration exposures to workers using these forks for beach cleaning.

Methods: Eight operators were recruited to operate the motorized forks during this laboratory study. Four fork configurations were used in the study; two motor speeds and two fork basket options were evaluated. Accelerations were measured near each hand as the operators completed the simulated beach-cleaning task.

Results: The dominant vibration frequency for these tools was identified to be around 20 Hz. Because acceleration was found to increase with motor speed, workers should consider operating these tools with just enough speed to get the job done. These forks exhibited considerable acceleration magnitudes when unloaded.

Conclusions: The study results suggest that the motor should not be operated with the fork in the unloaded state. Anti-vibration gloves are not effective at attenuating the vibration frequencies produced by these forks, and they may even amplify the transmitted vibration and increase hand/arm fatigue. While regular work gloves are suitable, vibration-reducing gloves may not be appropriate for use with these tools. These considerations may also be generally applicable for the use of motorized forks in other workplace environments.

Keywords: exposure estimation; HAVS; musculoskeletal injury; risk assessment; vibration

INTRODUCTION

In the summer of 2010, representatives from the National Institute for Occupational Safety & Health (NIOSH) joined in the response to the massive Deepwater Horizon oil spill in the Gulf of Mexico. Although some NIOSH teams concentrated on off-shore operations, some traveled to the gulf coast to perform exposure assessments, toxicity testing, health surveillance, and to provide guidance for protecting workers involved in beach-cleaning operations (NIOSH/OSHA, 2010). Whereas the on-shore teams focused on heat-stress prevention, fatigue prevention, and the use of respirators and other personal protective equipment, they also observed a number of risk factors for musculoskeletal disorders for workers using rakes, shovels, and improvised hand tools to manually remove tar balls and patties from beach sand. Some of these response workers expressed a preference for using the vibrating forks instead of the manual tools. However, it is unknown whether the hand-transmitted vibration (HTV) exposures associated with these vibrating forks are potentially hazardous; the literature review for this study

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uncovered no information on the vibration characteristics of these tools.

Continued occupational exposure to HTV has been related to an array of disorders in the vascular, sensorineural, and musculoskeletal structures of the hand-arm system (Griffin, 1990). These disorders have been collectively defined as hand-arm vibration syndrome (HAVS) (Taylor and Brammer, 1982). Even though the detailed mechanisms of HAVS are not fully understood, it is generally accepted that the development of the syndrome is primarily affected by vibration magnitude, frequency, and exposure time (Griffin, 1990). Therefore, evaluations of these factors are required in the standardized assessment of HTV exposure (ISO 5349-1, 2001a).

Unfortunately, it is very difficult to reliably characterize HTV exposures in field environments such as those found on the gulf coast. Alternatively, the vibration characteristics of these forks can be identified and quantified in a carefully developed laboratory-based work-task simulation. With knowledge of the vibration exposure characteristics, acceptable daily exposure times for these forks can be estimated based on the HTV exposure limits recommended in the European Union (EU) Directive 2002/44/EC (EU, 2002) and the American National Standards Institute (ANSI) S2.70 (2006) standard for assessing exposures to vibration. While the International Organization for Standardization (ISO) has developed a series of standards for laboratory-based screenings of various powered hand tools (e.g. ISO 28927-10, 2011), no such laboratory-based assessment exists for vibrating forks or similar long-handled tools.

Therefore, the objectives of the study were to (i) develop a laboratory-based methodology for characterizing HTVs of vibrating manure forks, (ii) use the developed methodology to characterize the vibrations associated with the use of those forks in a simulated beach-cleaning operation, and (iii) to derive appropriate vibration exposure time limits based on the EU Directive (EU, 2002) and the ANSI standard (ANSI, 2006). We hypothesize that motor speed, fork-loading condition, fork-basket configuration, and acceleration-measurement location will all influence measured acceleration magnitude.

METHODS

The detailed protocol for this study was approved by the NIOSH Human Subjects Review Board. A total of 8 adults (4 male, 4 female) were recruited locally to operate the forks in this study. None of the subjects were experienced fork operators. Each operator's sex, age, weight, and stature are presented in Table 1. The fork operators read and signed a consent form prior to their participation.

The apparatus for the vibrating manure fork testing is pictured in Fig. 1. The test apparatus consisted of a mortar-mixing tub filled with a fairly homogenous mixture of moist sand and debris (pine bark mulch and golf balls).

The vibrating forks evaluated in this study were Shake'n Fork™ models manufactured by Equi-Tee Manufacturing (Oregon, USA). Two fork models were evaluated in the study. One featured a variable-speed motor with a rated top speed of 980 rpm (referred to as the slow fork in this report); the second fork (fast fork) had a variable-speed motor with a rated top speed of 1400 rpm. The two models featured identical fiberglass handles. There were two different basket arrangements evaluated (see Fig. 2). One basket was molded from yellow flexible plastic; the second basket was black flexible plastic and featured a section of wire screen (6-mm mesh) attached to its tines. Both baskets featured 12.5-mm tine spacing. The forks/baskets are interchangeable, so with two motor speeds and two basket options, there were four different tool configurations evaluated in the experiment. Each fork configuration weighed 1.8 kg.

Prior to testing, there was a short practice session (about 5 min) to allow the operators to become familiar with the simulated work task and to get them accustomed to the timing sequence.

Table 1. Ages, weights, and statures of the four females and four males who served as tool operators in the study.

ID	Sex	Age (yrs)	Stature (m)	Weight (kg)
U	F	20	1.68	59.1
N	F	19	1.68	61.4
E	F	22	1.59	57.7
A	F	23	1.65	61.8
Z	M	30	1.83	102.3
S	M	39	1.78	61.4
Q	M	22	1.85	88.2
L	M	23	1.83	68.2

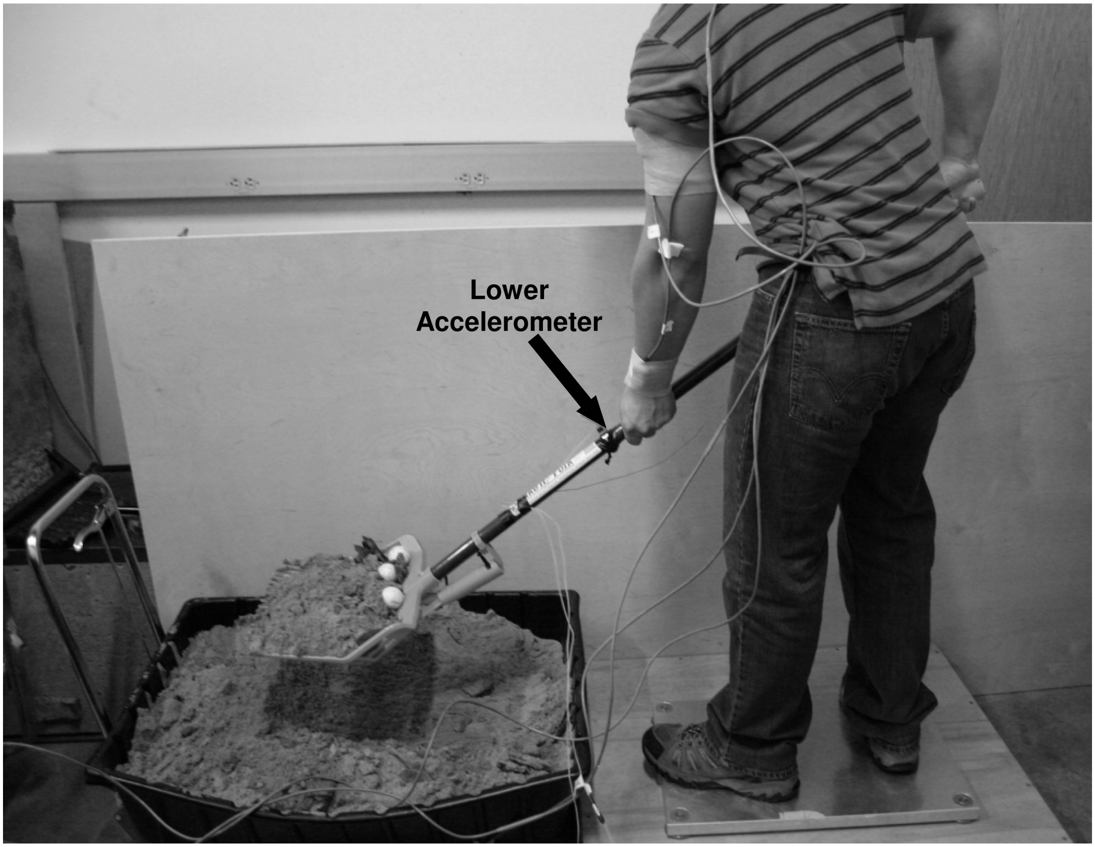

Fig. 1. Simulated beach-cleaning operation using a vibrating manure fork. Acceleration was measured at two points on each fork handle. The mounting position for the lower accelerometer is shown here. The upper accelerometer can be seen in Fig. 3.

To complete the simulated work task, the operator used one of the forks to scoop sand and debris out of the mortar-mixing tub. Typical operator posture is depicted in Fig. 1. As shown, the operator stood on a platform-mounted force plate and used a two-handed posture to control the fork. The operator placed their dominant hand on the upper handle. The operator used their non-dominant hand to support the fork handle near its midpoint. Prior to each trial, the fork operator stood still on the force plate holding the empty fork. The force plate reading was then zeroed. Next, the fork operator inserted the fork basket into the tub, scooped a load of sand and debris, and lifted the loaded fork 0.3 to 0.5 m directly above the tub. A test engineer then adjusted the amount of sand and debris in the basket until the force plate registered 50 ± 5 N. Once the load was weighed, the operator was signaled to start the fork's shaker motor by fully depressing the tool's handle-mounted trigger (see Fig. 3). After about 12 s, the operator was instructed to release the trigger, dump any remaining sand and debris back into the tub, and to rest. During the rest period, the test engineer raked the sand and debris in the tub in order to maintain a fairly homogenous mixture.

For quantifying HTV exposures, standardized vibration exposure assessments prescribed in EU Directive 2002/44/EC (EU, 2002) or the ANSI S2.70 standard (ANSI, 2006) use frequency-weighted acceleration as the basis for the measurement. However, in order to provide a more complete picture of the exposures, this study reports both frequency-weighted and unweighted acceleration measurements for each fork configuration. The four fork configurations (2 speeds × 2 baskets) were presented to the subjects in random fashion. Each fork configuration was subjected to a measurement sequence consisting of eight consecutive trials. The first five trials in the sequence were completed with the basket loaded; the next three trials were completed in the same fashion except with an empty basket. Each loaded trial consisted of scooping a forkful of sand and debris from the tub, lifting the fork directly above the tub, and triggering the shaker

Fig. 2. The two interchangeable baskets evaluated in the study. The black version on the left featured a wire screen (6-mm mesh) for sifting finer material.

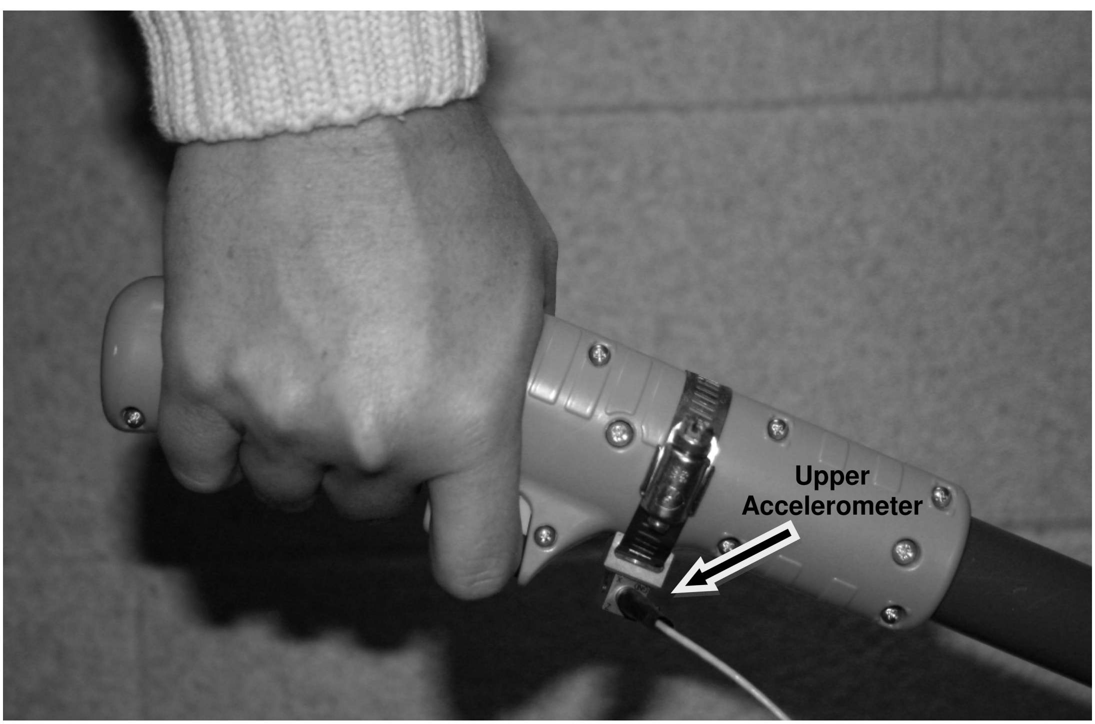

Fig. 3. The handle-mounted trigger used to control the shaker motor and the accelerometer mounted on the upper part of the handle.

motor to separate the debris from the sand. The fork operator was prompted when to trigger the shaker motor and when to release the trigger. Vibration data were collected during the shaking sequence. The fork vibrated for about 12 s per trial; the vibration data collected during the middle 8 s were used in the data analysis. The fork operator rested for at least 90 s between trials. Once eight trials were completed with a particular motor/basket combination, the next motor/basket configuration was prepared and presented to the operator. The operator rested for three to 5 min between motor/basket configurations while the fork was being prepared. The sequence was repeated until all four configurations were tested.

Two PCB Piezotronics, Inc. piezoelectric triaxial accelerometers (Model 356B11) were used to measure the vibrations at the tool surface. The accelerometers were mounted to the tool using hose clamps and accelerometer mounting blocks. The lower accelerometer was affixed near the midpoint of the tool handle just below the operator's non-dominant hand (see Fig. 1). The upper accelerometer was affixed near the handle-mounted trigger (see Fig. 3). Triaxial vibration data were collected via a portable six-channel Brüel & Kjær PULSE system featuring Input/Output Module Type 3032A. The vibration data collected from this system were expressed as the root-mean-square (rms) unweighted values of the accelerations in the 24 one-third-octave frequency bands, with center frequencies from 6.3 to 1250 Hz.

As outlined above, each fork configuration underwent a vibration measurement sequence consisting of five consecutive trials. Per trial 8 s of vibration data were collected. The 'total' values of the rms accelerations were computed using the following formula:

$$a_{h(rms)} = \sqrt{a^2_{hx(rms)} + a^2_{hy(rms)} + a^2_{hz(rms)}}\ , \quad (1)$$

where $a_{h(rms)}$ is the unweighted root-sum-of-squares total value, and $a_{hx(rms)}$, $a_{hy(rms)}$, and $a_{hz(rms)}$ are the unweighted rms values for the *x*-, *y*-, and *z*-axis, respectively.

To determine the ISO frequency-weighted acceleration values, an Excel spreadsheet was used to apply the frequency-weighting factors given in Annex A of ISO 5349-1 (ISO, 2001a):

$$a_{hw(rms)} = \sqrt{\sum_{j=1}^{24} (K_j a_{h,j})^2}\ , \quad (2)$$

where $a_{hw(rms)}$ is the frequency-weighted rms acceleration, K_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 rms accelerations were multiplied by their respective weighting factors, and the resultant weighted rms accelerations were determined for each axis. Then, as with the unweighted acceleration, the total ISO frequency-weighted values were computed using

$$a_{hv(rms)} = \sqrt{a^2_{hwx(rms)} + a^2_{hwy(rms)} + a^2_{hwz(rms)}}\ , \quad (3)$$

where $a_{hv(rms)}$ is the ISO frequency-weighted root-sum-of-squares total value, and $a_{hwx(rms)}$, $a_{hwy(rms)}$, and $a_{hwz(rms)}$ are the ISO frequency-weighted rms values for the *x*-, *y*-, and *z*-axis, respectively.

A general linear model analysis of variance (ANOVA) was conducted for ISO frequency-weighted acceleration ($a_{hv(rms)}$) to determine the significance of four fixed factors: fork speed (fast or slow), basket configuration (tines only or with wire-mesh screen), loading condition (loaded or unloaded), and accelerometer mounting position (upper or lower). The ANOVA was performed using SPSS 15.0 for Windows. Factors were considered to be statistically significant at the $p < 0.05$ level.

The experimental setup used in this study was designed to closely simulate the beach-cleaning operations observed in the field. While the vibration measurements collected in the laboratory may not be fully representative of actual work exposures, the ISO frequency-weighted tool handle vibration measurements ($a_{hv(rms)}$) may be used to estimate HTV exposures for vibrating fork users in real beach-cleaning operations. Estimated daily vibration exposure values, A(8), can be calculated using the methods outlined in ISO 5349-2 (2001b) and ANSI S2.70 (2006). The standard equation for estimating A(8) values is

$$A(8) = a_{hv(rms)} \sqrt{\frac{T}{T_0}}\ , \quad (4)$$

where *A(8)* is the daily vibration exposure in ms^{-2}, $a_{hv(rms)}$ is the total ISO frequency-weighted vibration magnitude (see equation 3 above), *T* is the total daily duration of the exposure (in hours), and T_0 is the reference duration of 8 h.

The international (ISO 5349-2, 2001b) and US (ANSI S2.70, 2006) standards offer guidance for applying this standard equation to different exposure situations. For the beach-cleaning tasks associated

Table 2. Operation time limits (T) for each fork configuration to remain below the EU/ANSI daily exposure action value ($DEAV$) of 2.5 ms^{-2} and the daily exposure limit value ($DELV$) of 5.0 ms^{-2}. Times are based on the weighted acceleration ($a_{hv(rms)}$) measured at the lower fork accelerometer with the forks in the loaded condition.

Motor	Basket	$\mathbf{a_{hv}}$ (m/s^2)	T_{DEAV} (min)	T_{DELV} (min)
Fast	Wire mesh	13.10	17	70
Fast	Tines only	26.89	4	17
Slow	Wire mesh	4.14	175	702
Slow	Tines only	8.27	44	175

with this study, the most appropriate method for determining the A(8) values is presented in section E.2.3 of Annex E of ISO 5349-2 (2001b). Briefly, the average frequency-weighted vibration magnitude $a_{hv(rms)}$ is calculated from several short-term measurements over intermittent periods of continuous tool operation. Then, the exposure time, T, is determined by quantifying the time in which the tool is actually running during the work shift. This value can be determined through worker observation, data logging, or other appropriate means.

Once the exposure time per 8-h shift is determined, A(8) values can be estimated using the above equation. These estimated A(8) values can then be compared to the daily exposure action and limit values prescribed in the EU Directive (EU, 2002) and repeated in Annex A of the ANSI standard (ANSI, 2006).

The EU Directive (EU, 2002) and ANSI standard (ANSI, 2006) have established a daily exposure action value (DEAV) of 2.5 ms^{-2}. According to the ANSI standard:

> The DEAV represents the health risk threshold to hand-transmitted vibration. For the purpose of this standard, health risk thresholds defined as the dose of hand-transmitted vibration exposure sufficient to produce abnormal signs, symptoms, and laboratory findings in the vascular, bone or joint, neurological, or muscular systems of the hands and arms in some exposed individuals.

The ANSI standard further states that when the daily exposure action value is exceeded, 'a program to reduce worker exposure to hand-transmitted vibration should be initiated to reduce health risks'. The standard provides guidance for such a program in Annexes B and C of the standard.

The EU Directive (EU, 2002) and ANSI standard (ANSI, 2006) have also established a daily exposure limit value of 5.0 ms^{-2}. Workers exposed to HTV at or above the daily exposure limit value 'are expected to have a high health risk'. The standard recommends that workers not be exposed to vibrations above the limit value.

Because no information regarding exposure times of the Deepwater Horizon oil spill response workers is known, it is not possible to estimate A(8) values for those workers. However, the ISO frequency-weighted tool handle vibration measurements ($a_{hv(rms)}$) from this laboratory study were used to estimate the maximum amount of exposure time per 8-h work shift that a user could operate a particular vibrating fork configuration without exceeding the EU/ANSI daily exposure action value of 2.5 ms^{-2} (EU, 2002; ANSI, 2006). The daily exposure action value time limit, T_{DEAV}, is calculated for each fork configuration using the following formula:

$$T_{DEAVi} = 480\left(\frac{2.5}{a_{hvi}}\right)^2, \tag{5}$$

where T_{DEAVi} is the time, in minutes, that a user could operate a particular fork configuration during an 8-h work shift without exceeding the EU/ANSI daily exposure action value, and a_{hvi} is the average frequency-weighted acceleration measured with that fork configuration.

In similar fashion, maximum exposure times that a user could operate the four vibrating fork configurations without exceeding the EU/ANSI daily exposure limit value, T_{DELV}, of 5.0 ms^{-2} were also calculated from

$$T_{DELVi} = 480\left(\frac{5.0}{a_{hvi}}\right)^2, \tag{6}$$

where T_{DELVi} is the time, in minutes, that a user could operate a particular fork configuration during an 8-h work shift without exceeding the EU/ANSI daily exposure limit value, and a_{hvi} is the average frequency-weighted acceleration measured with that fork configuration (EU, 2002; ANSI, 2006).

RESULTS

The average unweighted one-third octave band acceleration spectra measured by the upper and lower accelerometers was determined for each of the four fork configurations. The average spectra for the loaded trials ($n = 40$) are presented in Fig. 4. As can be seen, the dominant or fundamental frequency for each fork configuration is around 20 Hz, which is slightly higher than the frequency corresponding to the rated top speed of the slow fork (16.3 Hz at 980 rpm) but lower than that corresponding to the rated top speed of the fast fork (23.3 Hz at 1400 rpm). As expected, the second major peak occurs around 40 Hz, which doubles the fundamental frequency.

The frequency-weighted acceleration means ($a_{hv(rms)}$) for the upper and lower accelerometers are presented in Fig. 5. Fig. 6 presents the unweighted acceleration data ($a_{h(rms)}$).

Factors influencing fork vibration

Separate ANOVAs were performed for frequency-weighted and unweighted acceleration, but the conclusions from the two analyses were the same; fork motor speed, basket configuration, loading condition, and accelerometer mounting location are all significant factors influencing measured fork vibration ($P < 0.001$ for each factor). As can be seen in Figs 5 and 6, the mean acceleration for the fast fork motor was significantly higher than that for the slow motor; the vibration magnitude for the fast fork was found to be about three times that of the slow version. The tines-only basket produced roughly twice the acceleration magnitude of the basket with the wire-mesh screen. Acceleration magnitude was two to three times higher for the unloaded forks as compared to the loaded forks. As also shown in the figures, the accelerometer mounted on the lower end of the fork measured about twice as much vibration as the upper accelerometer.

Further analyses were performed to examine the effects of gender and operator body weight on fork vibration magnitude. The mean frequency-weighted acceleration was 14.1 ms^{-2} for females and 13.2 ms^{-2} for males. For unweighted acceleration, the means were 30.5 and 29.0 ms^{-2} for females and males, respectively. Although the differences between the male and female means are relatively small, they are both statistically significant ($P < 0.001$). The results of a Pearson correlation analysis indicate that increased operator body weight suggests reduced fork vibration. However, the correlation was not statistically significant ($P = 0.06$).

Exposure limitations based on laboratory acceleration measurements

Table 2 presents the estimated amount of time a particular fork configuration could be operated before reaching the daily exposure action value (T_{DEAV}) and daily exposure limit value (T_{DELV}), values set forth in the EU Directive (EU, 2002) and ANSI standard (ANSI, 2006). These times were calculated using equations 5 and 6 above based on the vibration measurements from the accelerometers mounted on the lower ends of the tool handles. These values are representative of the HTV exposures to the non-dominant hand in simulated beach-cleaning operations; the HTV exposures to the non-dominant hand were found to be considerably higher than those to the dominant hand. As indicated, the tines-only fork with the fast motor could be operated for only 4 min at maximum speed before reaching the EU/ANSI daily exposure action value of 2.5 ms^{-2}. On the other hand, the slow fork with the wire-mesh basket could be operated at full throttle for nearly 3 h during a shift before reaching the daily exposure action value.

DISCUSSION

The vibrations of four configurations of typical lightweight, battery-powered, motorized vibrating manure forks were measured in this study. Although the measurement was conducted under a simulated working condition, the results are applicable for understanding the basic vibration characteristics of these forks and to provide a first approximation of the exposure levels of workers in beach-cleaning operations using these forks.

This study found that these motorized forks primarily generate sinusoidal vibrations with dominant vibration frequencies around 20 Hz. Therefore, they are classified as low-frequency (<25 Hz) vibration tools. Because the vibration emissions of such tools result from imbalanced rotational motions of the motor, the vibrations are non-percussive and without substantial high-frequency components. Their high-frequency peaks occur at multiples of the fundamental frequency. These observations are confirmed by the spectra shown in Fig. 4. There is little to no epidemiological evidence to indicate that such tools are associated with vibration-induced white finger (Griffin, 1990; Tominaga, 2005). And though low-frequency percussive tools have been linked to bone and joint disorders (Gemne and Saraste, 1987), non-percussive tools have not been implicated in the causation of such disorders. These observations

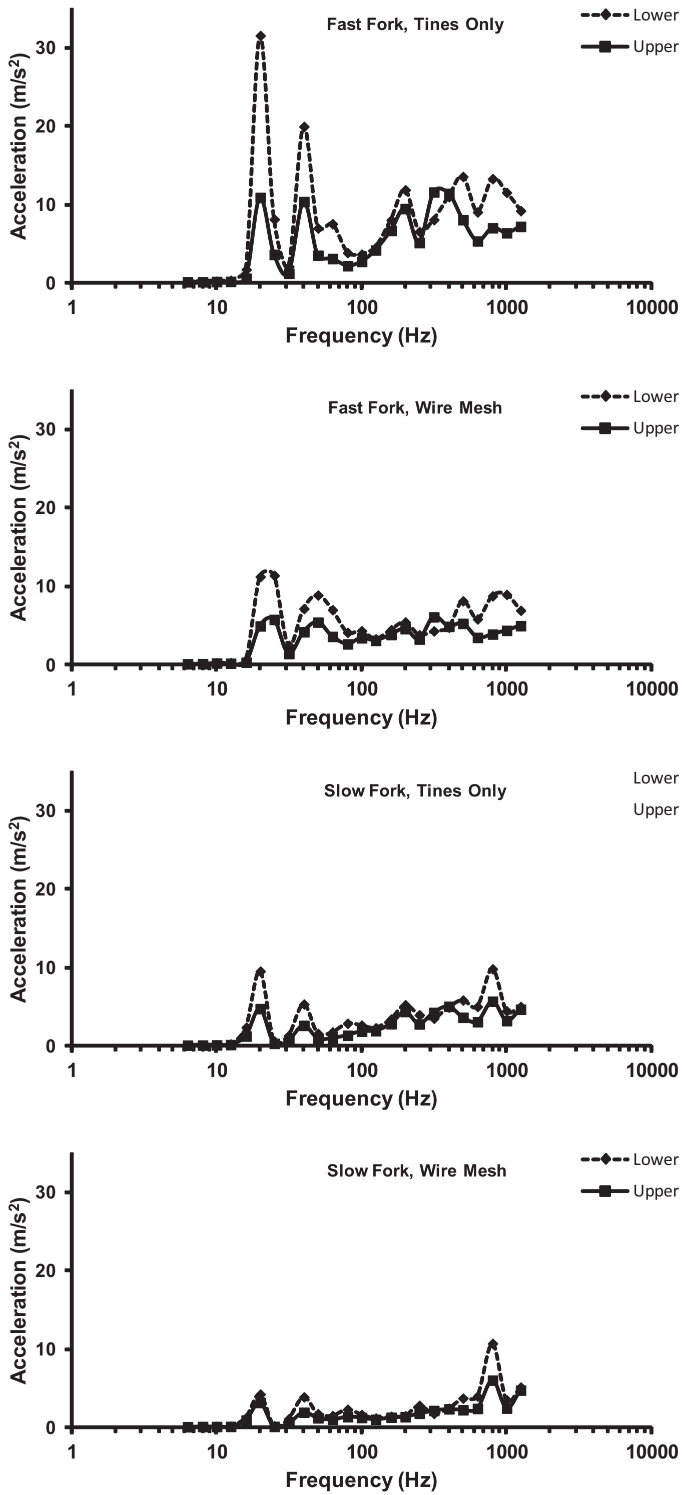

Fig. 4. Unweighted one-third octave band acceleration spectra for each of the four fork configurations in the loaded condition measured with the upper and lower accelerometers.

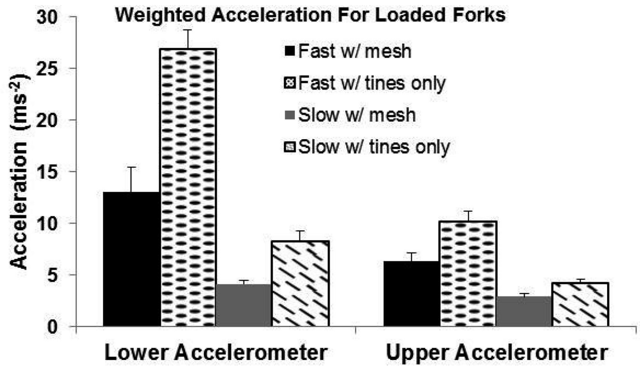

Fig. 5. Frequency-weighted acceleration for the four fork configurations measured with the upper and lower accelerometers. (Error bars equal +1 SD.)

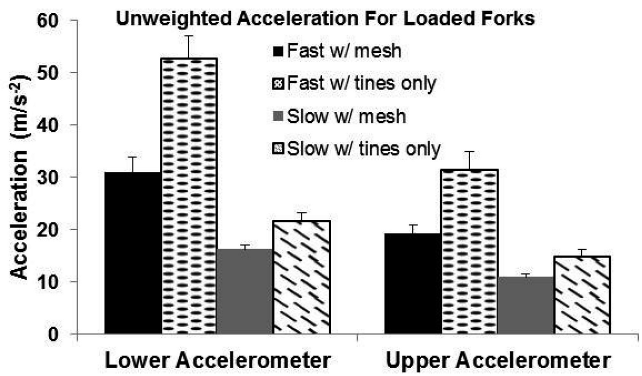

Fig. 6. Unweighted acceleration for the four fork configurations measured with the upper and lower accelerometers. (Error bars equal +1 SD.)

suggest that the vibration exposures associated with these motorized forks are unlikely to lead to a significant prevalence of vibration-induced musculoskeletal disorders among fork operators. However, the dominant vibration frequency of these motorized forks falls in the frequency range in which the entire hand-arm system has been found to be the most sensitive (Miwa, 1968). Such low-frequency vibration can be effectively transmitted to the entire hand-arm system as well as the neck and head; a high magnitude of such vibration could lead to considerable discomfort, especially in the arms (McDowell *et al.*, 2007), which may indicate a risk of other ergonomic concerns.

Because the frequency weighting defined in the current international standard ISO 5349-1 (ISO, 2001a) is derived from subjective sensation data, frequency-weighted acceleration is an acceptable measure for assessing the potential for discomfort in the hand-arm system. The results of this study indicate that the frequency-weighted accelerations of these forks could be substantial in some cases. The 8-h equivalent exposure action value (2.5 ms^{-2}) and limit value (5.0 ms^{-2}) recommended in the ANSI standard (ANSI S2.70, 2006) or required in the EU Directive (EU, 2002) are applicable for controlling discomfort associated with fork vibration exposures; in any case, the exposure to fork vibration should be controlled at the lowest possible level.

According to equation 4, there are two basic approaches to controlling vibration exposures: (i) reduce the magnitude of the vibration exposure; and (ii) reduce the time of the exposure. The results of this study indicate that vibration magnitude increases with motor speed. Thus, an effective way to reduce vibration magnitude is to operate the variable-speed motors of these forks at the lowest speed possible to complete the task. Of course, there is a trade-off associated with operating the forks at lower speeds; the vibration exposure period increases due to the extra time necessary to separate the debris from the sand. However, as indicated in Table 2, an operator could use a slow fork for roughly ten times as long as a fast fork and experience the same frequency-weighted acceleration exposure. Thus, our results indicate that operating a slower fork for more time is generally favorable to operating a fast fork for a short period. This is especially true when decontaminating dry sand because under relatively dry conditions, a slow fork is nearly as effective as a fast fork. The results also show that fork vibration was significantly higher for unloaded forks as compared to loaded forks. This suggests that the motor should be operated as little as possible when the forks are unloaded; this will reduce both vibration exposure magnitude and time.

Vibration-reducing gloves have been increasingly used to help reduce HTV exposures (Welcome *et al.*, 2012). However, vibration-reducing gloves are not effective for reducing low-frequency vibrations. In fact, vibration-reducing gloves can actually amplify low-frequency vibrations, especially in the neighborhood of 20 Hz (ISO 10819, 1996; Dong *et al.*, 2004; Welcome *et al.*, 2012). Such gloves can also reduce grip strength by more than 30% and require more grip effort (Wimer *et al.*, 2010), which could result in early fatigue of the hand and arm. Alternatively, regular work gloves can protect the hands from sun exposure, cuts, and abrasions without introducing substantial grip-strength reduction. In cold work environments, wearing work gloves in the operation of vibrating forks is also useful for keeping the hands warm and dry, which in turn reduces the potential for the development of HAVS. This may not be important for the operation of motorized forks at warm beaches, but it may be very important for the operations of these forks at farms, stables, and other workplaces in cold climates.

It should be noted that all of the measurements in this study were collected with the fork motors operating at maximum speed. As indicated in the ANOVA results, faster motor speeds result in significantly higher accelerations. In actual beach-cleaning operations, these tools are not always operated at full speed. Furthermore, the forks are seldom operated without a load. Thus, actual HTV exposures in the field may be lower than the values reported here. The weighted acceleration ($a_{hv(rms)}$) values for the lower handle accelerometer (mounted near the non-dominant hand) presented in this report can be considered as 'worst case' values.

During many of the loaded trials with the fast fork motor, much of the load was sifted through the basket before the 8-s data-collection period was completed. Because the acceleration values were averaged over the entire 8-s periods, the vibration averages for the loaded fast forks actually include vibrations produced under very light loading conditions. In actual beach-cleaning operations, fork users will typically release the trigger once the debris is sufficiently separated from the sand. In many cases, the sifting process will take much less than 8 s. Furthermore, the sand that was used in this laboratory study was fairly damp. In many cases, beach sand will be much drier than what was used in this study, and dry sand will be sifted much more quickly than damp sand. Thus, the vibration measurements for the forks presented here may not be representative of typical HTV exposures encountered during the Deepwater Horizon oil-spill cleanup or other beach-cleaning operations.

On the other hand, during many of the loaded trials with the slow fork, most of the load remained in the basket at the end of the 8-s data-collection period. This was especially true for the basket with the 6 mm wire-mesh screen. Furthermore, all of the fork operators in this study had difficulty using the basket featuring the wire mesh to scoop the sand mixture out of the tub. Because of this problem as well as with the extended trigger time required to clear the basket with this configuration, it appears that the slow motor/wire mesh basket configuration is ill-suited for beach-cleaning operations, especially when damp sand is involved. However, the load specified for this laboratory study is likely considerably larger than a typical load for this type of fork used in actual beach-cleaning operations.

Despite these disclaimers, the frequency-weighted acceleration data presented here suggest that these vibrating forks are likely to produce daily exposure values, or A(8) values, greater than 2.5 ms^{-2} during beach-cleaning operations. To be consistent with the guidance provided in Annex C of the ANSI S2.70 standard (ANSI, 2006) and Articles 6 and 8 of the EU Directive 2002/44/EC (EU, 2002), whenever any sign of HAVS such as prolonged numbness of the fingers and hand, joint pain, or muscle weakness appears after the operation of a motorized fork, the workers should seek medical attention.

CONCLUSIONS

The vibration exposures from motorized forks will vary with fork model and configuration. The vibration emissions of any given fork will depend primarily on the fork load and motor speed. In some cases, over the course of an 8-h shift, the frequency-weighted daily exposure values, or A(8) values, associated with the tested fork models are likely to exceed the daily exposure action value (2.5 ms^{-2}) or limit value (5.0 ms^{-2}) defined in the ANSI S2.70 standard (ANSI, 2006) and the EU Directive 2002/44/EC on vibration exposures (EU, 2002). Because these vibrating forks are low-frequency (<25 Hz), non-percussive tools, they are unlikely to cause serious finger disorders such as vibration-induced white finger, or lead to any major damage to the bones or joints of the hand-arm system. However these motorized forks could cause considerable discomfort. Therefore, the vibration exposures should be controlled as much as possible. The findings of this study suggest that the following control methods be considered:

- **Limit run time.** Operators of motorized forks should reduce the amount of 'trigger time' to short bursts that are just sufficient to separate the debris from the beach sand.
- **Operate the forks at the lowest possible speed.** The forks are equipped with variable-speed motors. Faster operating speeds results in higher vibration exposures. These forks should be operated with just enough speed to get the job done; it is usually not necessary to fully depress the trigger.
- **Do not operate the forks unloaded.** The mass of the loaded basket helps to dampen the vibration. These forks should not be operated in the unloaded condition.
- **Do not use vibration-reducing gloves with these tools.** However, regular work gloves are suitable for use with these tools.

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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